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THESIS

WIND PROFILER STUDY OF THE CENTRAL CALIFORNIA SEA/LAND BREEZE

by

Jeffrey D. Stec

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Thesis Advisor:	Carlyle H. Wash
Second Reader:	Wendell A. Nuss

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WIND PROFILER STUDY OF THE CENTRAL CALIFORNIA SEA/LAND BREEZE

Jeffrey D. Stec
Lieutenant, United States Navy
B.S., United States Naval Academy, 1987

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of the requirements for the degree of

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ABSTRACT

Sea/land-breeze events on the Monterey Bay are examined using data from the 915-MHz wind profiler and RASS systems. These sensors were deployed during Jun-Aug 1994 in conjunction with the REINAS Project conducted by various scientific institutions in the region. Data analyzed are continuous radar and virtual temperature returns located at four sites strategically positioned around the bay. This relatively new remote sensing device provides information on maximum/minimum sea/land-breeze heights, onset and cessation times, virtual temperature distribution with height, and the effect of mountainous coastal topography on the sea and land breeze system.

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I. INTRODUCTION

The diurnally reversing winds commonly referred to as the sea/land breeze is perhaps one of the most familiar atmospheric phenomena. Since a large percentage of the world population lives near coastal areas, a better understanding of sea-breeze circulations will impact positively on a variety of civilian and military activities. Sea-breeze circulations play an important role in affecting both civilian and military coastal aviation operations. Low stratus and fog associated with the sea breeze seriously influence aircraft operations. Thick fog, common during autumn evenings along the California coast, force arriving aircraft to be diverted to alternate airports. Abrupt changes in temperatures in the coastal regions due to the sea-breeze result in varying payload characteristics of both jet aircraft and helicopters. Changing direction of the prevailing winds also affect the orientation of the duty runways. Since some runways do not have certified instrument approach radars this may result in more diverts to alternate airfields.

In some locations, a cool afternoon sea breeze is a refreshing relief from stagnant heat. At another location, a sea breeze brings pollutants inland from an urban area. These pollutants can cause harmful concentrations of toxic gases. The population of Los Angeles is all too familiar with the photochemical smog trapped in the cool marine air that settles over their region.

Sea-breeze circulations also have important effects on agriculture and forestry. Some crops benefit from the high humidity coastal weather, which is brought in daily by the sea breeze. Garlic, lettuce, and artichokes, grown around Monterey Bay, have some of the highest crop yields per acre in the continental United States The water-deprived vegetation during late summer months is extremely susceptible to fires. A sea-breeze moving over a forest fire can create a dangerous situation. Unpredictable gusty surface winds often make the fire difficult to control. An understanding of sea-breeze circulations is required by fire fighters to prevent the spreading of fires once they are started.

This thesis examines the sea-breeze structure for the Monterey Bay region and focuses exclusively on data from June-August 1994. This thesis follows previous studies of the sea-breeze events done in the Monterey Bay region, specifically, the studies by Round (1993), Yetter (1990), Intrieri et al. (1990), Banta et al. (1993), and Fagan (1988). In this study, the 915-MHz wind profiler and Radio Acoustic Sounding System (RASS) is used to explore the vertical structure of the sea breeze. The marine environment is an ideal location for the profiler. Higher levels of moisture content in the atmosphere allow high vertical ranges for the profiler because the air will have higher refractive index variations. The UHF wind profilers, first used in central U.S. in the late 1980's for thunderstorm studies, provide a new look at sea-breeze structure. The vertical profile of the wind direction and speed overlaid with virtual-temperature data are available continuously during the day and night.

The study will use data from four different stations: Santa Cruz, Hollister, Pt Sur, and Ft Ord-(Fritsche Airfield). These four stations are geographically spaced at useful locations in order to interpret the mesoscale-scale sea-breeze circulation in the Monterey Bay area. The characteristics of the particular land-breeze days, sea-breeze days and the effect of the synoptic scale influence on the mesoscale-scale sea-breeze circulation, also are examined. Finally, this thesis inspects the compensatory return flow in a strong sea-breeze day. The return flow was difficult to detect in earlier studies and hopefully with the continuous profiling measurements of the clear-air radar, this study will be able to better document its existence

II. BACKGROUND

In this study of the sea-breeze, first the general characteristics of this thermally induced phenomena are reviewed. Secondly, other important factors influencing the sea-breeze circulation along central California are discussed including previous research in the Monterey Bay region. A discussion of the basic forcing mechanisms and modifying factors provides needed background information to interpret the results of this thesis. Since this study is conducted on the central California coast, emphasis is placed upon the coastal topography and the synoptic scale forcing.

A. THERMALLY INDUCED CIRCULATIONS

The sea/land breeze is a thermal circulation that develops at the coastal boundary, where there are large differences in the radiative properties of the water and land surfaces. The basic forcing mechanism that drives the sea-breeze circulation is the development of a coastal thermal gradient. The land surface absorbs the sun's radiation much more efficiently than the water. These specific radiative properties directly influence the overlying atmosphere contained in the land and marine boundary layers. During the daytime hours surface heat flux is transferred into the land boundary layer while the marine boundary layer remains cool. At night the thermal gradient is reversed because the much warmer land surface radiates more long wave radiation upward while the water loses heat at a much slower rate. This reversal of the thermal gradient sets up the nocturnal land-breeze. Thus, we see the circulation going through a diurnal cycle just due to the differing radiative properties of the land and water (Atkinson, 1981).

A more concentrated thermal gradient will result in a stronger coastal pressure gradient The effect of temperature difference on the pressure-gradient force is most conspicuous in coastal areas where the difference in the radiative properties of water and land produce large temperature gradients over a short distance. Figure (2.1) from Blair and Fite (1965) illustrates how differential heating induces pressure variations. The differential heating develops a surface temperature gradient and associated surface pressure gradient. High pressure over the water surface and low pressure over the land creates a pressure-gradient force that causes the daytime onshore flow we commonly referred to as the sea breeze. Horizontal pressure-gradient forces aloft over the land push the air outward from the land as indicated by the arrows in Figure (2.1). It should be noted that the land breeze circulation is not as intense as the sea breeze either in velocity or depth. This is because the lower heat source is weaker and does not carry the circulations to greater heights as with the sea breeze (Atkinson, 1981).

B. MODIFYING FACTORS THAT AFFECT THE DIURNAL HEATING CYCLE

Since thermally-induced circulations, such as the classic sea breeze, are dependent upon the absorption or reflection of incoming solar radiation, it is useful to examine some modifying effects to the earth's insolation. The most conspicuous modifying effect is the time of year. This is especially important in middle and high latitudes regions where the sun's seasonal inclination is profoundly felt. In the summertime, the longest daylight hours provide more heating of the land surface. The more shortwave radiation absorbed by the land will result in a more concentrated thermal gradient and thus a stronger sea breeze

The latitude of a region is crucial in calculating the amount of solar insolation

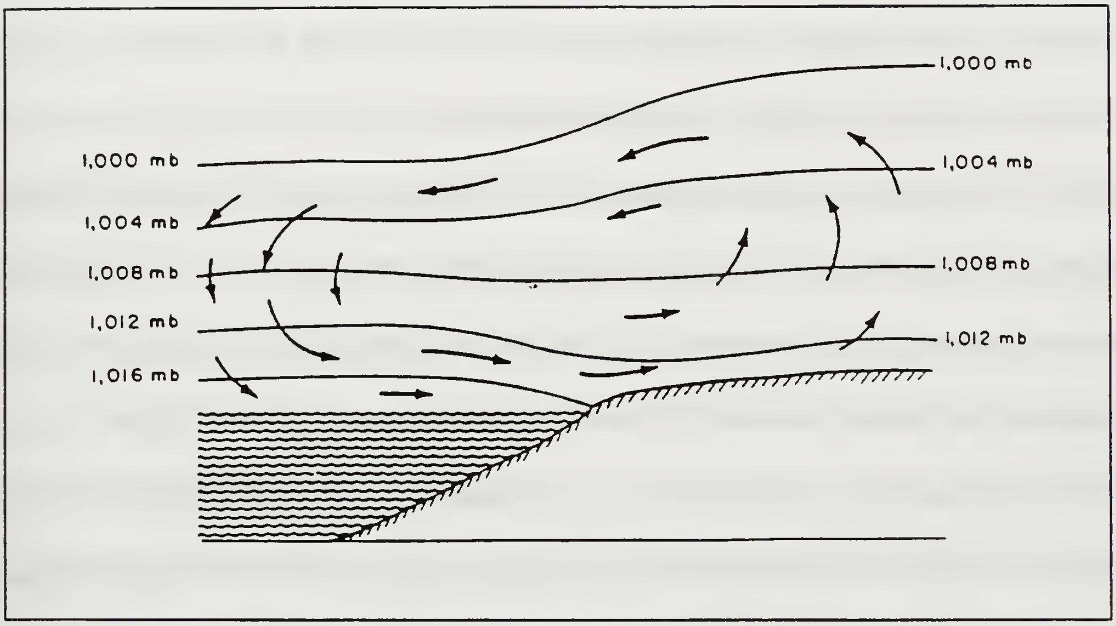

FIGURE 2.1. This Sea-Breeze schematic demonstrates the upward bending of the isobars over the land and the subsequent seaward flow of the upper air. Completing this circulation , low-level air over the sea is flowing landward (from Blair and Fite 1965).

received. At coastal locations in low latitudes the sea/land-breeze pattern is present on almost all days throughout the year, but at higher latitudes the received insolation may be unable to generate a strong enough thermal-gradient to offset the larger-scale wind systems. The strength of the sea/land-breeze circulation at low latitudes due to increased solar heating is found in many studies.

Clouds reflect and absorb insolation reducing the amount of short-wave radiation available for surface heating. For a cloud-covered surface, the loss of short-wave radiation is greater than the gain of long wave radiation causing a net loss of energy at the surface. Reduction in the daytime surface temperature in cloudy regions causes a corresponding decrease in the magnitude of the surface turbulent heat fluxes (Segal et al., 1986). Marine stratocumulus clouds that are common on the central Californian coast, are characterized by a high reflectivity (albedo) and thus land surface heating is greatly reduced by their presence. The numerical model evaluations by Segal et al., (1986) showed that "sea-breeze circulation intensities may be reduced by as much as a factor of two when the incoming solar radiation at the surface is 40% of its value for clear-sky conditions. (Such a modification in the solar radiation at the surface is typical during overcasts.)" An earlier study by Wexler (1946) determined that the two most dominant conditions for favorable sea-breeze circulation production were clear skies and light winds. These two factors allow sufficient surface heating to prevent the sea-breeze from being overwhelmed by the background flow. Wexler (1946) identified a percentage of existence of the sea-breeze circulation at Burgas, Bulgaria during various cloud conditions:

Scattered clouds (0-5 tenths) = 90%

Broken clouds (6-9 tenths) = 39%

Overcast clouds (10 tenths) = 27%

Another modifying factor to the diurnal heating cycle is the amount and type of vegetation. A detailed study by Segal et al., (1992) noted that in an ideal situation of an extended, dense, and fully transpiring vegetated area adjacent to dry land, the corresponding surface sensible heat flux values of the vegetated areas were as low as ~ 50 W\m^2. This is equivalent to the surface sensible heat flux determined for water surfaces with light-to-moderate winds (Kondo, 1975). Dense vegetation areas with high transpiration rates juxtaposed next to dry land areas can produce "nonclassical mesoscale circulations" that are close in intensity to the more traditional sea breezes (Segal and Arritt, 1992). Coastlines that are dry and barren such as rocky volcanic islands heat up more quickly than most well-vegetated ones given the same radiative input of energy. As a result, more heat becomes available to initiate the sea-breeze circulation on barren coastal areas. Regions with vegetation remain cooler at the surface compared with arid areas because of evapotranspiration from plants and wet soil evaporation.

Many studies have been done to document the differences in surface air temperature between irrigated areas and dry-land areas. Barnston and Schickedanz (1984) studied the development of "islands" of irrigated areas in the western Great Plains of the United States during the years' 1939-69. In the eastern Texas Panhandle, they found that irrigation appears to lower the daily maximum summer air temperature about 2 °C during synoptically undisturbed periods. Investigating the impact of vegetation cover on the intensity of the south Florida summer sea breeze, McCumber (1980) ran a three dimensional numerical model His sea-breeze simulations consisted of one case using dry bare soil and the other case using wet soil covered with dense vegetation. He found that in the case with dense vegetation, increased evapotranspiration rates led to a reduction in the surface sensible heat flux. Consequently, the sea-breeze intensity was reduced significantly in strength (peak values of u and w within the simulated cross section are reduced to around 2 m/s and 3 cm/s, respectively, Segal et al, (1988).

The vegetation in the Monterey Bay area is of a varied nature. Areas under cultivation receive copious amounts of irrigation thus cooling the surface air temperature through evapotranspiration and wet soil evaporation. The areas not used for growing crops are either urban areas or areas covered with naturally occurring vegetation. The natural vegetation mainly consists of resilient plants such as chaparral that are robust enough to exist in central California's dry Mediterranean like climate. The natural vegetative cover will assist the sea-breeze in it's initiation due to its large surface sensible heat flux. The greatest chance for a "nonclassical mesoscale circulation", as previously discussed by Segal and Arritt (1992), occurring in the Monterey Bay region would be in the Salinas Valley. It is here where heavily cultivated lettuce and broccoli fields are juxtaposed next to the dry infertile slopes of the Sierra de Salinas and Gabilian Ranges. This vegetative induced thermal gradient combined with the normal upslope afternoon flow can join together to give the sea breeze a positive increase in intensity.

The depth of the planetary boundary layer greatly affects the strength of the thermal gradient at the surface. A deep planetary boundary layer with lots of vertical mixing will not experience an equal amount of warming for a given amount of surface heating than a shallow boundary layer (Nuss, 1992). A low planetary boundary layer with a strong inversion at the top would favor a strong sea-breeze circulation. A strong inversion layer will retard any vertical mixing with the upper atmospheric layers. During the summer in central California, a strong subsidence inversion often exists with the warm air aloft that is approximately 15 °C warmer than the underlying coastal marine layer. The combined effects of the cold, upwelling surface waters offshore and the strong tropospheric subsidence under the semi-permanent subtropical high pressure system located off the Pacific Coast are responsible for this strong inversion. Along the Texas Gulf coast and the coasts of Florida, where much of the scientific study of the sea breeze has been done, deeper planetary boundary layers exist. These East Coast planetary boundary layers result in more vertical mixing and a decrease in the surface thermal gradient. The capping inversions in these East coast regions are weaker with the air aloft being approximately 5°C warmer than the air near the surface. Sometimes upward vertical motions are strong enough to break through these capping inversions further reducing the coastal surface temperature gradients.

C. GRADIENT (LARGE SCALE) FLOW

The gradient or large scale flow has important modifying effects on local sea/land-breeze circulations. When the gradient winds are onshore, the horizontal temperature gradient from land to sea is reduced. Therefore, this weakens the sea-breeze development. Depending on the strength of the land breeze, an onshore gradient flow can prevent its development or cause sharpening of the temperature gradient at the leading edge of the land breeze (Atkinson, 1981). Considering gradient winds flowing parallel to the coastline, Wexler (1946) felt that a sea breeze would rarely develop. Later studies would substantiate that parallel gradient flow causes little hindrance on the development of sea/land breezes (Frizzola and Fisher, 1963). With offshore gradient winds, the strongest sea breezes are produced. These mesoscale circulations start over the sea and slowly advance landward usually not reaching the coast until mid-afternoon. If the offshore gradient winds reach a certain magnitude they may prevent the formation of any sea breeze. Kimble et al., (1946) investigated sea/land breezes off the island of Java in Indonesia and concluded that an offshore wind exceeding 15 kts would prevent the formation of a sea breeze. Frizzola and Fisher (1963), making observations in New York City, found an opposing flow of 15 to 20 kts and a land-sea temperature difference of less than 10°F will in cases prevent the penetration of the sea breeze inland.

The above relationships between the large scale flow and the local sea breeze have been reproduced by the numerical model studies of Estoque (1962) and Arritt (1993). The model used by Estoque (1962) in his classic study assumed a 5 m/s synoptic wind. Arritt expanded on this earlier study by examining a broader range of onshore and offshore synoptic winds. He used 31 numerical simulations using imposed synoptic-scale geostrophic winds of ug= -15, -14, -13,...13, 14, 15 m/s. By keeping all his initial conditions besides the large-scale flow the same for each simulation, Arritt ensured the results are due specifically to the effect of the imposed large-scale flow. From the database of his 31 sea-breeze simulations, Arritt (1993) concluded that onshore synoptic flow of not more than 3 m/s was sufficient to suppress the thermally induced circulation. However, for offshore synoptic flow as strong as 11 m/s, the sea-breeze was still apparent

Arritt (1993) classified sea-breeze dependence on synoptic flow into four categories:

1) **Onshore synoptic flow:** When the large-scale flow is in the same direction as the sea-breeze, the result is a weakened thermal perturbation of the large-scale flow.

2) **Calm to moderate opposing synoptic flow:** This regime is associated with the most intense sea-breezes. The intensity of the thermally induced perturbation increases for stronger opposing flow.

3) **Strong opposing synoptic flow:** Vertical motions in the sea-breeze are suppressed and horizontal velocities are also weakened, but to a lesser degree.

4) **Very strong opposing synoptic flow:** In this case the vertical velocities and the horizontal temperature gradient are weak. There is no sea-breeze.

Arritt's work confirmed earlier studies that the stronger ambient stratification led to a weaker sea-breeze. His linear solutions demonstrated that stable stratification over the water suppresses both the u (horizontal cross-coast) and w (vertical) components of the sea-breeze circulation. Evidence for the existence of a sea-breeze circulation entirely offshore was also noted in strong opposing flow conditions. It may be possible for coastal areas to be influenced by sea-breeze convection even if there is not any onshore flow at the coastline. However, this offshore sea-breeze is weaker than the canonical sea-breeze that reaches the coastline. It's vertical velocities are small thus reducing its ability to trigger deep convection

The study concluded noting that the most favorable synoptic conditions for thermally induced circulations occur when the ambient wind is light in magnitude and opposite in direction to the induced circulation. The opposing flow aids in the concentration of the thermal gradient while flow in the same direction as the circulation tends to disperse or weaken the thermal gradient necessary for the thermally induced flow.

D. FRICTION

The interaction of the sea/land breezes with ocean and terrain surfaces result in friction. The sea-breeze circulation is generally contained within the planetary boundary layer (typically below 1000 m). Above the planetary boundary layer the wind is approximately geostrophic.

The frictional characteristics over water and over land are markedly different. The sea surface is aerodynamically smooth while the earth's surface is a fully rough aerodynamic surface (Sutton, 1953). Therefore, once the sea breeze crosses the sea-land interface surface frictional influences are going to become more of a factor. Because of friction, surface winds move more slowly than geostrophic winds with the same pressure gradient and surface winds also blow across isobars toward lower pressure. The frictional drag of the ground normally decreases as we move away from the earth's surface. Wexler (1946) observed that this effect of friction may cause the sea breeze to appear aloft before it becomes evident at the surface. Ahrens (1994) determined that the frictional influence in the boundary layer is primarily dependent on three factors:

1. Surface heating that provides strong thermal turbulence and a steep lapse rate.
2. Strong wind speeds that produce strong mechanical turbulent motions.
3. Rough or hilly landscape that produces strong mechanical turbulence.

When all these three factors combine simultaneously, the frictional effect is transferred up vertically high enough to effect all aspects of the sea-breeze circulation

Haurwitz (1947) reasoned that frictional effects must play an important role in the sea-breeze circulation. He understood that without friction, Bjerknes' circulation theorem predicts the maximum onshore wind would occur near sunset instead of at the observed mid-afternoon time. His study showed that, owing to the effect of friction, the maximum sea-breeze intensity occurs not when Tl (land temperature) - Tw (water temperature) decreases to zero but earlier, while the land is still warmer than the sea. The effect of friction requires a positive temperature difference just to overcome the frictional force. Once the Tl - Tw difference falls below this critical value, friction starts to act as a braking mechanism. Stronger frictional effects, i.e., more hilly terrain, requires a higher critical temperature difference between sea and land to maintain a sea-breeze. Additionally, this stronger friction reduces the time between maximum temperature differences (Tl - Tw) and the time we see the maximum intensity of the sea-breeze circulation. From this reasoning we can conclude that in central California where the coastal mountains cause increased frictional barriers we can expect to find a greater temperature difference (Tl - Tw) required to initiate a sea breeze than an area such as Texas's Gulf coast where the coastal terrain is relatively flat.

E. CORIOLIS FORCING

The theoretical analysis by Haurwitz (1947) was the first study to show dynamically that the Coriolis force can explain the diurnal turning of the sea and land breezes. This clockwise turning of the sea breeze in the northern hemisphere is demonstrated in the surface wind hodograph at Logan Airport in East Boston, Massachusetts in Figure (2.2)

Further studies by Neumann (1977) showed that the rate of directional rotation of the sea/land breeze is not constant over the diurnal cycle. Data from various areas of the world corroborate that rotation rates are high in the morning and in the late evening. During the other periods of the diurnal cycle, the rotation rates are slower. Although the rate of wind turning due solely to the earth's rotation is constant, the interaction of the flow with the horizontal pressure gradient force and frictional forces results in differing rates of directional rotation throughout the sea/land-breeze cycle. Kusuda and Alpert (1983) showed that strong pressure gradient flow in areas such as the lee of mountains can be so large to offset the Coriolis parameter and actually cause a counterclockwise or backing rotation in the northern hemisphere.

For Coriolis force to have appreciable effect on sea/land-breeze circulations, an air parcel must remain in the circulation for an extended period of time. Since the Coriolis effect is not instantaneous like the pressure gradient force, it needs time to exert it's influence. The closed circulation would increase the time Coriolis force has to act, thus causing veering motions in the northern hemisphere. Hsu (1970) conducted a observational study on the Texas gulf coast to see if the directional turning could occur throughout a continuous diurnal cycle. He determined the sea/land breezes were turning a full 360° throughout the diurnal cycle Anthes (1978),using a two-dimensional mesoscale model, found Coriolis force was important in causing significant transport along the coast These alongshore displacements are comparable to the displacements normal to the coast. However, Coriolis force effects did not become significant until six

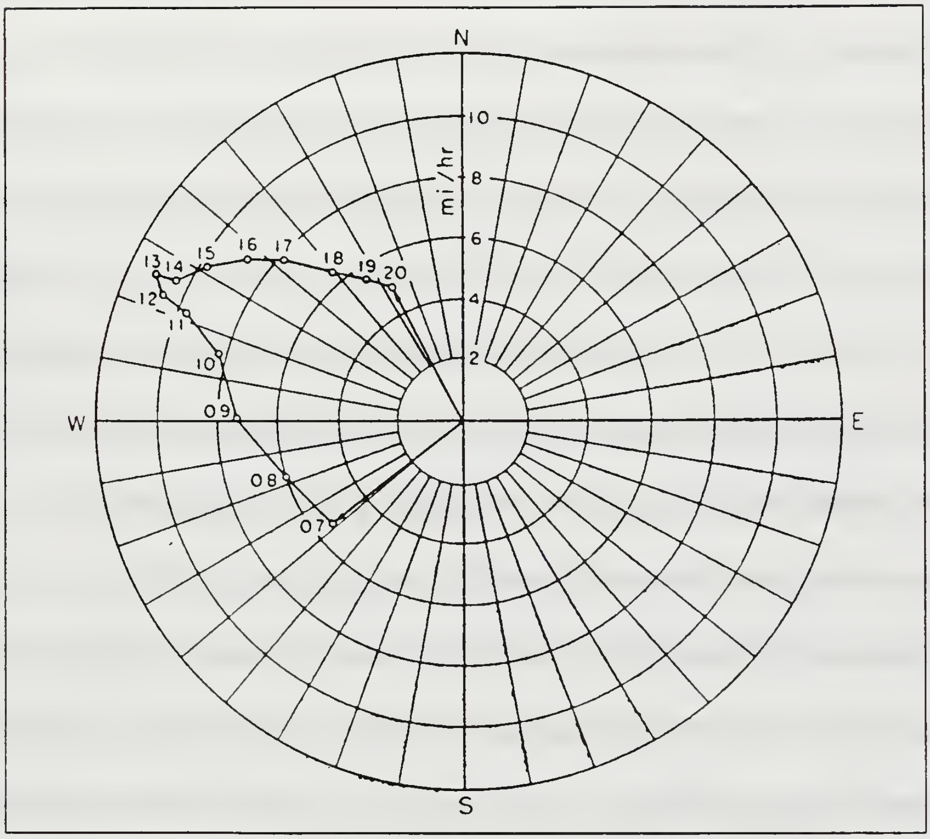

FIGURE 2.2 Mean winds during the sea breeze event at Logan Airport, East Boston, Massachusetts (based on 40 cases). Clockwise turning is clearly evident as the day progresses (from Haurwitz, 1947)

hours after the heating cycle began.

F. ROLE OF STABILITY

The stability of the atmosphere has a profound effect on the sea-breeze circulation. An atmosphere that is statically stable, i.e., cold air beneath warm air, tends to dampen the sea-breeze circulation by limiting it's vertical extent. Wexler (1946) noted that the most favorable time for sea-breeze penetration is the time of greatest vertical instability. The vertical motions in the sea-breeze circulation will relax the concentrated surface thermal gradient that starts the sea breeze. Adiabatic cooling in the rising air above the land and the adiabatic warming as the air descends vertically over the water both act to offset the horizontal thermal gradient. In a stable atmosphere, the upper stable layers damp the vertical circulation of the sea-breeze. Investigating both stable and unstable cases in their study of the Chicago lake breeze, Patrinos and Kistler (1977) found unstable air encourages an extension of the circulation both horizontally and vertically.

Johnson and O'Brien (1973) noted that a subsidence inversion associated with a high pressure system over the Oregon coast also restricts upward motion, which lowers boundary layer depth and effectively caps the depth of the onshore flow of the sea-breeze circulation. Estoque's (1962) model showed a stable thermal stratification decreases the intensity of the circulation as well as the depth of the landward flow. Recently, Arritt (1993) performed a controlled experiment using a two-dimensional sea-breeze model investigating the effects of ambient winds. In his experiment, he found that the strong stability associated with a subsidence inversion over water causes a weaker sea breeze

A strong stable stratification located below the subsidence inversion may weaken the vertical motion in the boundary layer as compared to a weakly stratified boundary layer. If the boundary layer is well mixed or unstable, a deep layer of strong sea-breeze winds will result. When the air below the inversion is stably stratified, it will force maximum intensities of the sea-breeze flow to remain aloft. The stratification of the air below the inversion undergoes considerable diurnal fluctuations due to the heating and cooling of the land surfaces. At nights the boundary layer stratification is stable and it becomes unstable in the early afternoon due to solar heating. This decoupling of the surface layer winds from the rest of the layer cause the land breeze at the surface to be rather difficult to detect (Nuss, 1992).

G. CONTINENT-OCEAN CIRCULATION

The mesoscale sea-breeze circulation along a continental coast can be embedded within a larger scale continent-ocean circulation. This continent-ocean circulation occurs over a much larger area than then coastal mesoscale sea-breeze circulations. In California, the unique topography of two different mountain ranges establishes a significant large scale diurnal temperature difference that drives this continent-ocean circulation. The temperature gradient is formed between the arid central valley and the cold ocean surface waters. The higher mountains of the Cascade and Sierra Nevada Ranges act as an effective barrier to any eastward penetration of marine air. The lower coast ranges such as the Santa Lucia mountains south of Monterey act as a partial barrier to marine air. Some marine air does enter California's central valley through low-level gaps in the coast ranges. However, the broad central valley normally experiences very little modification due to the cooling effects of the moist marine air. During the summertime in Fresno, California, the temperatures can exceed 40°C while coastal locations at the same latitude such as the Monterey Peninsula are enjoying comfortable 20 °C temperatures. Further offshore, the Ekman turning of the ocean surface causes cold sub-surface water to upwell and provides a strong cooling mechanism to the adjacent air in the marine boundary layer. In short, a significant diurnal temperature gradient is formed between the coastal ocean surface and the warm interior central valley. This large temperature gradient forces the large scale continent-ocean circulation.

Wexler (1946) observed this continent-ocean flow in his early study. He noted that in addition to the sea/land-breeze circulation that affects only the immediate vicinity of the coast, "there is a diurnal large scale continent-and-ocean wind thermally induced by the general temperature difference between the two areas." This large-scale wind is extremely light and spread throughout the troposphere and can only be detected statistically. Wexler labeled the wind that blows from the continent to ocean at night a "continent wind" and the wind that blows from the ocean to the continent by day an "ocean wind". He assigns values to the continent wind of 1 m/s and to the ocean wind ≥ 1 m/s. Examples of the continent-ocean wind where found between Cologne, Germany and the North Sea, and between Berlin and Valentia, Ireland. Wexler concludes by noting the depth of the flow for continent wind is 1300 m and ocean wind is ≥ 3 km respectively. A return flow aloft completes the continent-ocean circulation although values for strength and depth are not noted

In a later study by Johnson and O'Brien (1973), a continent-ocean circulation was detected off the Oregon coast. Using a set of meteorological observations obtained by using aircraft, pilot balloons, rawinsondes, and surface buoys, they were able to detect the existence of two scales of thermal forcing. The smaller scale forcing due to diurnal surface heating and cooling of the land, causes an intense temperature gradient between a surface buoy and a coastal station separated by 18 km. Values for the mesoscale circulation are as follows:

-temperature difference range between buoy and coastal station: -2 to +5°C

mean temperature difference: 1°C

temperature gradient: 5°C/20 km

On the larger scale of thermal forcing between an open ocean buoy and a interior valley station separated by 90 km, a smaller temperature gradient is seen:

-temperature difference range between buoy and coastal station: 2 to 11°C

mean temperature difference: 7°C

temperature gradient: 7°C/100 km

Johnson and O'Brien determined that this large scale continent-ocean circulation is more difficult to detect when it becomes embedded in the more intense local mesoscale circulation.

Schroeder and Fosberg (1966) described this same continent-ocean circulation as a monsoon flow. They found strong pressure and temperature gradients forming between the eastern Pacific subtropical high pressure area and the thermal low pressure in California's central valley. The subsiding air over the ocean capping a layer of marine air and the arid air inland characterize the summer climate in the central California coastal mountains. Concluding their study north of San Francisco during the summer of 1961 and 1962, Schroeder and Fosberg (1966) found the sea breeze was superimposed on this onshore monsoonal flow.

H. COASTLINE SHAPE

The geography of a coastline has a profound influence on the forcing of the sea-breeze circulation. Usually the sea breeze starts to move inland at right angles to the land boundary. If the coastline is straight, a nearly uniform sea breeze will move inland. However, if the coast is not straight, the sea breeze flow will converge or diverge according to the curvature of the coastline. A concave coastline, which Monterey Bay is a good example, causes a divergence of the onshore horizontal flow. The magnitude of the surface divergence occurring on the land side of the sea-land boundary is increased because of the diffluence of the cross-coast flow. This horizontal divergence also results in an asymmetric modification of the vertical branches of the sea-breeze circulation. The concave coastline results in a reduction in the intensity of the vertical updrafts and suppression of cloud formation in the sea-breeze front. A simple schematic illustration from Pielke (1984) is useful in exhibiting how the coastline shape effects the sea-land breeze flow (Figure 2.3).

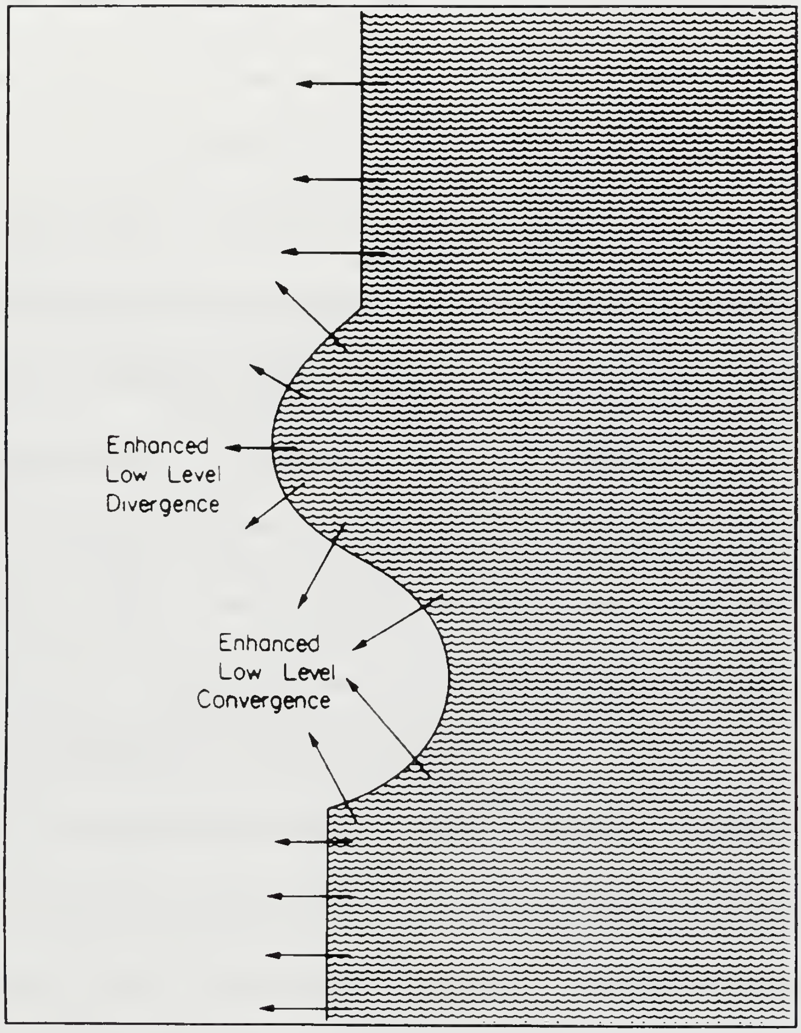

FIGURE 2.3 Schematic of the influence of coastline shape on the sea breeze in the absence of large-scale flow (from Pielke, 1984)

III. SEA BREEZE OF MONTEREY BAY

A. SYNOPTIC SCALE SITUATION OFF NORTHERN CALIFORNIA

The unique combination of physiographic and oceanographic features along the Pacific coast of northern California strongly effects the synoptic flow and ultimately the sea/land-breeze circulation. The dominant synoptic feature from late spring to early fall is a subtropical anticyclone located about 1000 km west of the California coast near 40 ° N. This semi-permanent feature is responsible for almost daily occurrences of coastal fog and low level stratus associated with a large-scale subsidence inversion over relatively cold ocean surface water. The water is coldest adjacent to the coast because of Ekman turning where prevailing summertime northwesterly gradient winds transport warmer surface water off the coast to be replaced by colder sub-surface water. The adjoining land area, under the influence of the eastern edge of the Pacific High, is subject to intense daytime heating. These two factors create a large coastal temperature gradient that is conducive for sea-land breeze generation (Beardsley et al., 1987 and others).

The large scale direction of the ambient winds in northern California are also affected by the position of the subtropical high. During the summer, the gradient winds are parallel to the coast or onshore due to the anti-cyclonic (clockwise) flow associated with a high pressure center located offshore. As a result of this typical summertime synoptic pattern, the classic sea breeze with a definitive frontal structure is not frequent. More common is a diurnal modulation of the prevailing northwest flow backing into a westerly flow during the late afternoon. These strong summertime onshore ambient winds make it difficult to distinguish the mesoscale sea breeze. Additionally, the land breeze during the summer months is difficult to detect because of the dominant northwest gradient winds mask out this offshore flow.

Round (1993) classifies the dominant type of sea-breeze circulation during the summertime in northern California to be the gradual development type. The gradual development type sea-breeze days include all days in which a definite sea breeze occurred without a clear and definite time of onset. Beginning in late September and early October, synoptic conditions produce an offshore flow that give us the more classic frontal sea breeze.

B. TOPOGRAPHY OF THE MONTEREY BAY REGION

Coastal ranges, depending on their orientation, can either accentuate or retard the sea-breeze circulation. Slope effects can enhance the local sea/land-breeze circulations since the shore naturally slopes upward from the sea to land. Daytime heating of the slopes heats the adjacent atmosphere causing the air to rise. Temperature and pressure gradients between the warm air over the slope and the cooler air over the lower elevations are thus created. In the afternoon when radiative heating has produced an upslope flow, the sea-breeze circulation can be superimposed over this flow creating an intensified sea-breeze. During the evening, the land breeze is aided by nocturnal cooling of the atmosphere above the slopes. Figure (3.1) provides a schematic diagram on how flow varies from the afternoon to the evening.

In Monterey Bay, topographical effects also limit the growth of mesoscale circulations simply by their presence. The gaps and valleys found in this region tend to

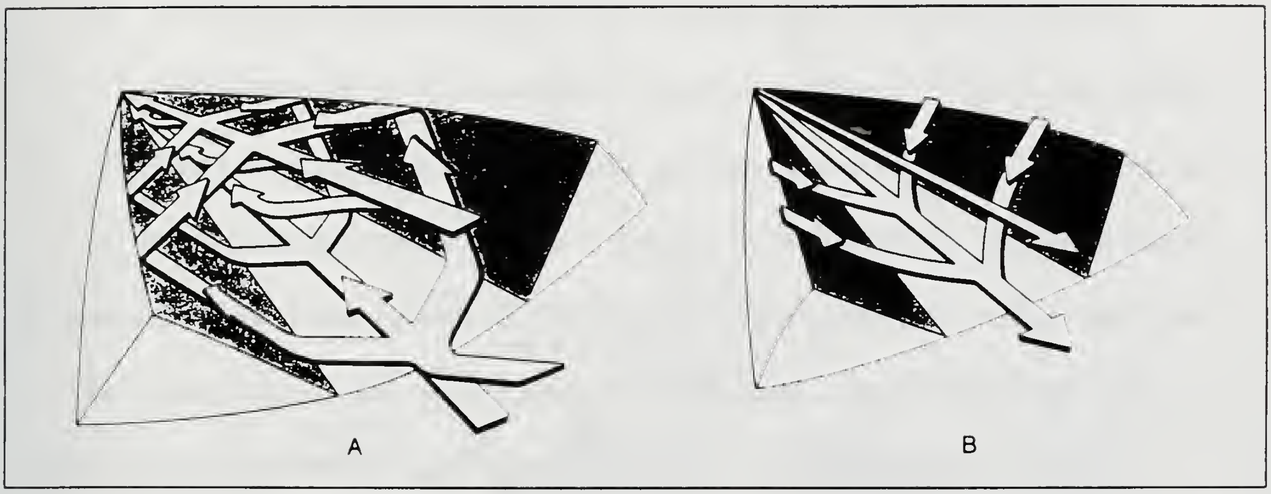

FIGURE 3.1 Schematic illustration of flow in a valley: (A) in the afternoon when heating is causing upslope winds; (B) around midnight when nighttime cooling forces flow down the valley and the slope (from Defant, *Compendium of Meteorology*, 1951, p. 665)

funnel sea-breeze flow. The study by Elliot and O'Brien (1977) recorded the profound effect that a coastal mountain range in central Oregon can have on the inland penetration of the sea breeze. The Monterey Bay region is somewhat different than central Oregon which is characterized by a relatively straight coastline and coastal mountains that are orientated parallel to the coast. The terrain in the Monterey is much more complex. As shown in Figure (3.2), the terrain varies from sea level to over 4,000 feet in the Santa Lucia Range.

The Santa Cruz Mountains are to the north and northeast of Monterey Bay. The Gabilian Range lies to the east and southeast. A gap exists 25 km east of Monterey between these two coastal ranges. Hollister, one of the profiler sites for this study, is located in this gap. Further east of Monterey (~ 55 km) is another gap that opens to the San Joaquin valley. This valley which encounters intense summer-time heating is bounded by the towering Sierra Nevada Mountains on the east and the Diablo Range on the west.

The most identifiable feature in the Monterey Bay region is the Salinas Valley. It is about 20 km wide at its mouth and extends 140 km to the southeast. The Gabilian and Sierra de Salinas form its eastern and western boundaries respectively. The Salinas Valley is important in the local sea-breeze circulation for not only channeling effects, but also to provide the heating required for sea-breeze initiation and intensification. Further to the southwest of the Salinas Valley are the Santa Lucia mountains. These mountains run parallel to the Pacific coast. The elevations of these mountains are the highest in the Monterey region with heights of 5,861 feet at the Junipero Serra Peak. This thesis will use data from a profiler site located at the Point Sur Naval Station (Refer to Figure 3.3). This is an ideal location to examine the topographical effect of a steep slope adjacent to the

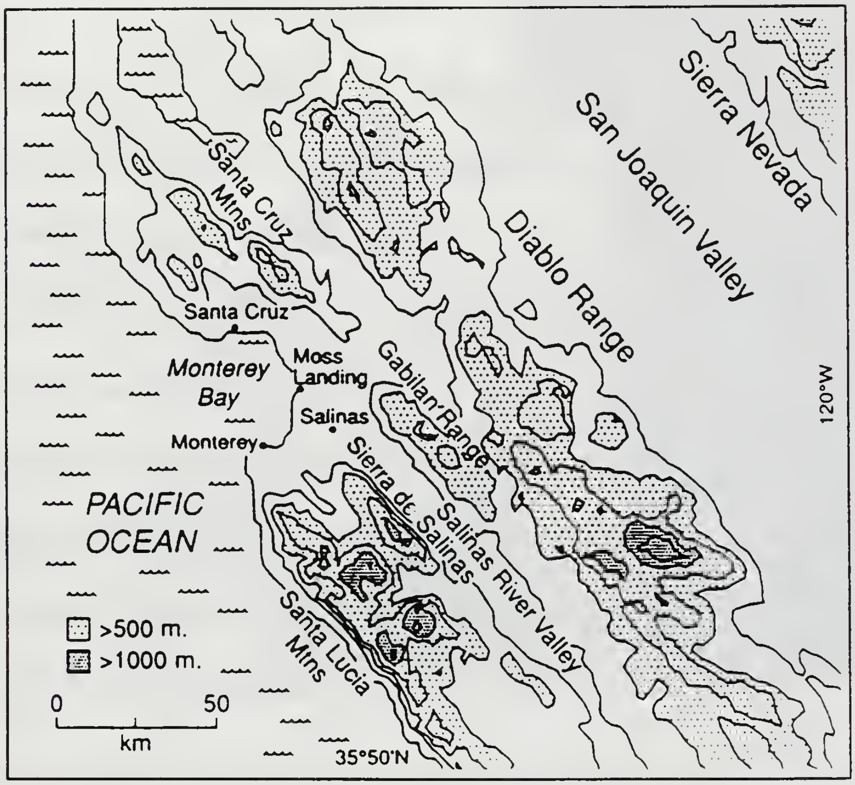

FIGURE 3.2 Topographical map of the Monterey Bay region The coastal mountains and the valleys impacting the coastal wind flows are shown. Terrain above 500 m has light shading and terrain greater than 1000 m has dark shading (from Banta et al . 1993)

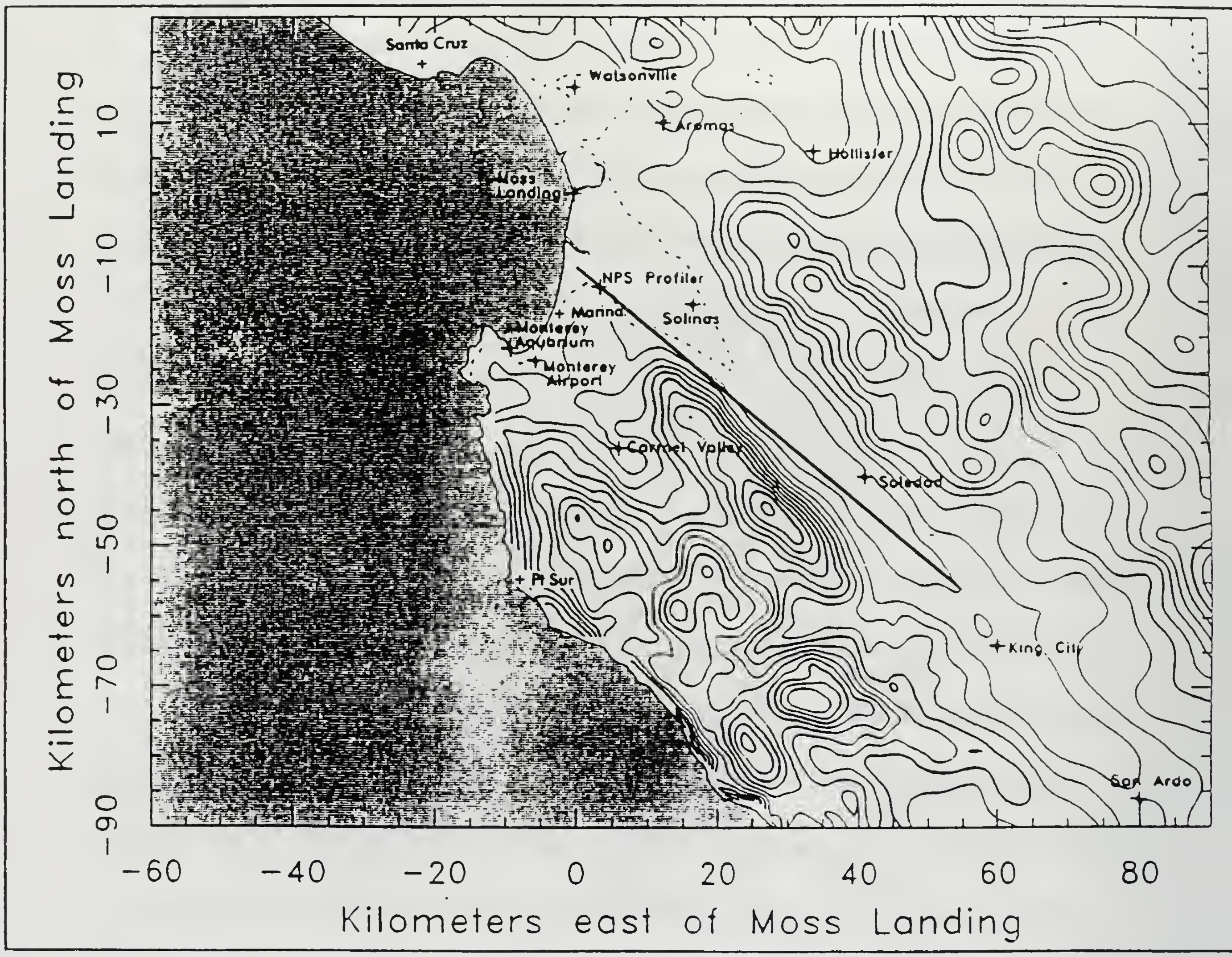

FIGURE 3.3 The terrain surrounding Monterey Bay. The Santa Lucia Mountains are to the south of the City of Monterery. Heavy line indicates onshore orientation in the Salinas Valley. The dashed line represen 50 meters above sea level, while the solid lines represent 100 meter contour intervals. 500 meter contours are highlighted in bold (from Round, 1993)

ocean

The mountainous coastline in Monterey will increase chances for an earlier sea-breeze onset compared to a relatively flat area such as Florida or the Texas's Gulf coast Normally a sea breeze is being forced in a direction perpendicular to the coastline. When a valley such as the one in Salinas is orientated at an angle relative to the coastline, the sea breeze may start to rotate into an along valley direction due to channeling effects. Previous studies have demonstrated that the sea breeze in the Salinas is steered in a direction that is almost parallel to the basic coastal orientation on the larger scale.

C. CLOUD EDGE IN SALINAS VALLEY

The modifying effect clouds have on the surface heat budget have been discussed previously in the background section of this thesis. Locally clouds play a pivotal role in Salinas Valley, where the concentration of the thermal gradient is transferred from the shore to further inland. During the night, clouds can penetrate past King City, which is located approximately at mid-valley or 70 km inland, to the upper regions of the Salinas Valley (Refer to Figure 3.3). The determining factor in how far the clouds penetrate is the depth of the marine layer. A shallow marine layer will have little penetration, while a deep marine layer could extend 140 km inland filling the whole valley. As the sun rises, solar insolation beyond the marine stratus warms the ground and overlying air forming a temperature discontinuity at the stratus edge. Later in the day, the stratus line recedes back toward the coast. A balance is attained between the cooler air underneath the clouds and the warmer air generated by cloud free skies. This balance routinely occurs at mid-valley causing the clouds to be situated at a stationary equilibrium position just to the southeast of the city of

Salinas. The cloud edge becomes a region of a concentrated thermal gradient. The modifying effects of not only the topography but more importantly the clouds, produce a inland region of winds more intense than at the coastal boundary (Nuss, 1992).

D. CONCAVITY OF MONTEREY BAY

Monterey Bay is a 40 mile wide distinct concave coastal feature. This concavity causes a divergence of the horizontal cross-coast flow. The dominant prevailing synoptic flow in central California during the summertime is from the northwest. This large-scale wind is geostrophic with the coastal mountains maintaining northwest flow.

The strongest sea-breeze is observed in Marina where both the northwest synoptic flow and the mesoscale flow combine to produce a large cross coast flow (Refer to figure 3.3). As this flow proceeds down the Salinas Valley it should encounter further clockwise turning. The profiler site at Fort Ord is in an optimal location (4 km from the coast), to observe any veering that may occur upon the sea-breeze frontal advance into the valley mouth. Further up the coast near the middle of the bay is Moss Landing. The magnitude of the resultant flow here is less than in Marina and with a more westerly heading. The Monterey Peninsula located at the southern part of the bay acts like a headland with convergent horizontal flow. Observations have recorded southwest flow blowing across Pt Pinos.

At the top of the Bay in the city of Santa Cruz, an interesting situation occurs. Here the water is the warmest in the bay, thus reducing the magnitude of the thermal gradient driving sea-breeze development. Additionally, Santa Cruz mountains create a blocking barrier to the northwest gradient winds. Historical observations in the city have documented predominantly onshore flow. Foster's (1993) study of the sea breeze in Santa Cruz for September 1992 found the mean monthly flow to be 2.0 m/s in an easterly direction. Some offshore or westward flow was detected between the hours of 0200 to 0700 PST. The monthly mean for this offshore flow during these nighttime hours was .77 m/s. Onshore flow, which was initiated after 0800 PST had a maximum peak at 1400 PST and a monthly mean of 6.8 m/s at this time. The close proximity of a ridge that lies adjacent to the city and runs parallel to the coast may help explain this lack of any significant offshore flow. The profiler site located in the city should provide some interesting data to explain this unique local phenomena.

E. ROUND'S SIX CASE STUDIES

Numerous studies have been done on the sea-breeze circulation in the Monterey Bay region. Using a single data station at Fort Ord, Round (1993) completed a detailed analysis of the sea-breeze behavior covering 183 days between April and September of 1992. This study evaluated each day manually and classified them into the following six categories: 1) no sea breeze, 2) gradual development sea breeze, 3) clear onset sea breeze, 4) frontal sea breeze, 5) double surge sea breeze, and 6) unclassifiable days. Sea-breeze day determination was accomplished using quantitative criteria with the following prioritization: 1) wind shift to the onshore direction, 2) wind speed increase $\geq$ 3 m/s in 30 minutes, 3) temperature drop > 1 ° C in 30 minutes and 4) a decrease in temperature-dew-point depression > 1 °C.

Days with no sea breeze either fell below the sea-breeze index of 5 m/s or through visual inspection of the station data lacked a definite wind shift, wind speed increase, drop in temperature or increase in dew point. The gradual development type of sea breeze forms with either the pressure gradient oriented parallel to the coast with resultant alongshore winds or with the pressure gradient perpendicular to the coast and light, onshore winds. Here the prevailing winds have a significant effect on the sea-breeze formation. This gradual type displays a more subtle onset of onshore flow. It includes all days in which a definite sea breeze occurred without a clear and definite time of onset. The clear onset type of sea-breeze circulation is very similar to the gradual development type differing only in the onset signal. This type includes all days in which either a definite windshift without a speed increase occurred or onshore wind conditions prevail to sea-breeze onset which is revealed by a distinct increase in onshore wind speed. The frontal type of sea-breeze circulation develops when the pressure gradient is oriented perpendicular to the coast with offshore winds and is distinguishable by definite frontal characteristics. This frontal type displays a more abrupt increase in wind speed and a easily distinguishable wind direction shift. The sea-breeze categorization term "double surge" includes all days in which two separate and distinct onshore events occurred. The final sea-breeze categorization is unclassifiable days. Round (1993) uses this classification to describe days in which the existence of clear characteristics could not be verified from the data.

Investigating the averages from Round's data we see that two categories dominate The histogram of sea-breeze category distribution shows that gradual development type sea-breeze occurs 36 percent of the time while the frontal type breeze is the next most common at 29 percent (Refer to Figure 3.4). Clear onset is the third most frequent

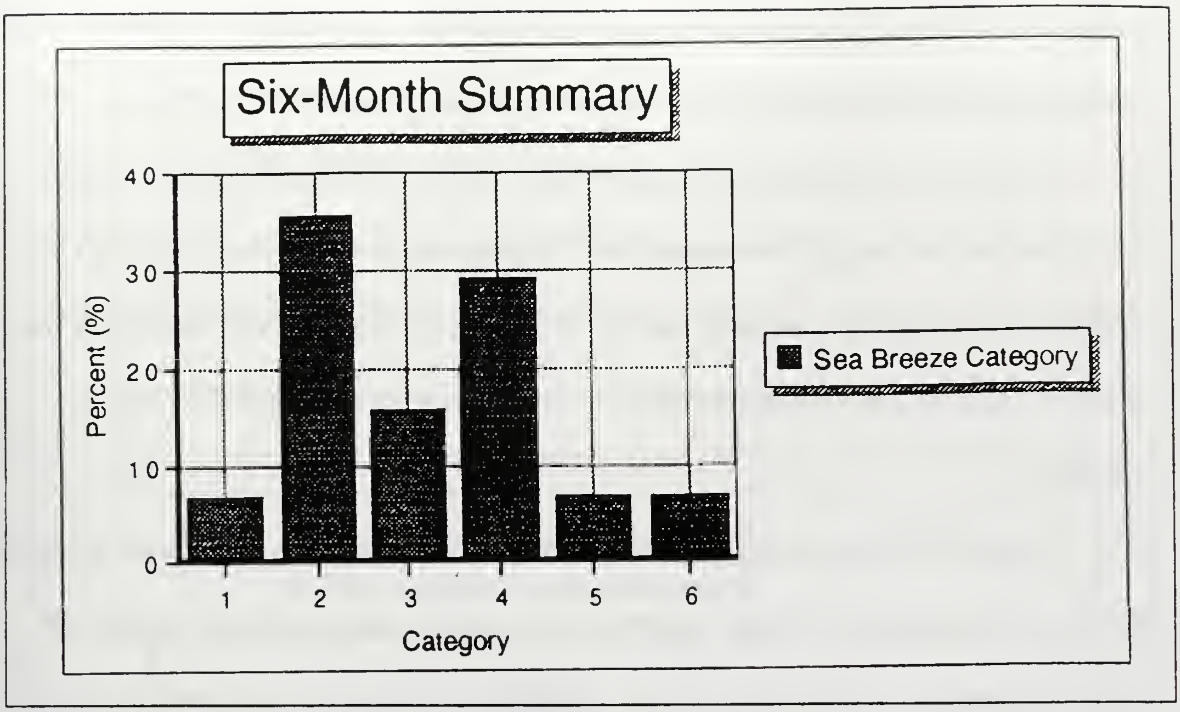

FIGURE 3.4 Six-month sea breeze category distribution at Fort Ord profiler site 1) No sea breeze, 2) gradual development, 3) clear onset, 4) frontal, 5) double surge sea breezes, 6) unclassified days (from Round, 1993).

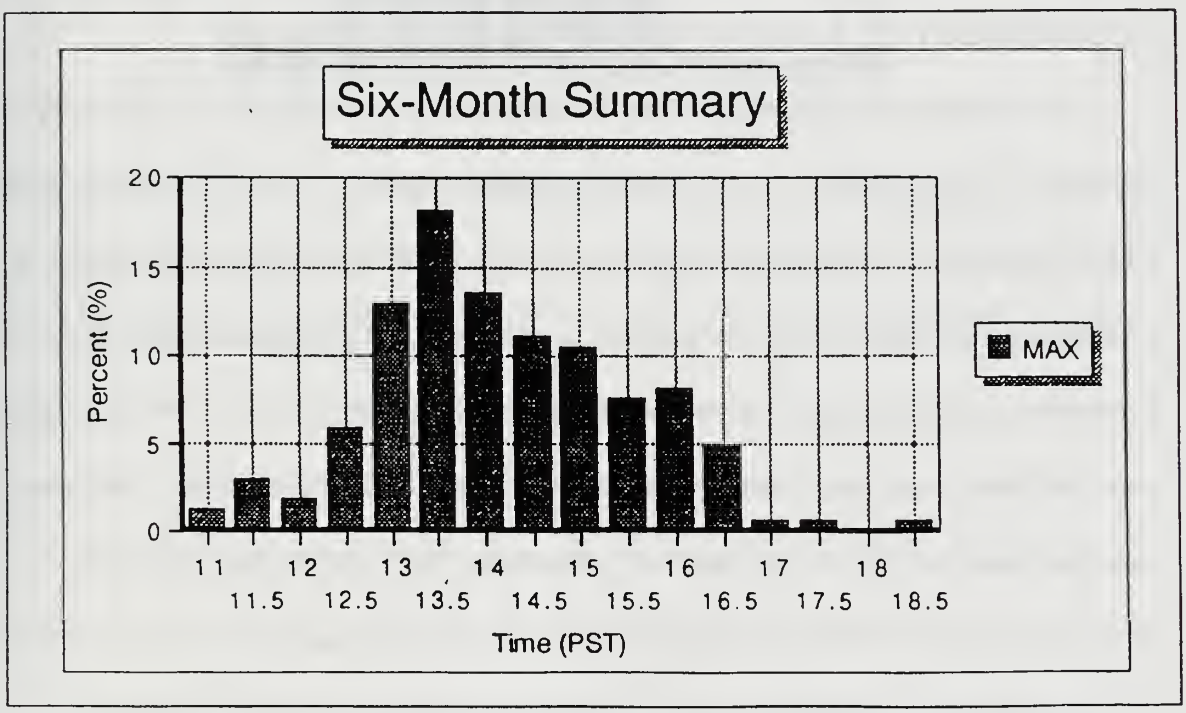

FIGURE 3.5 Six-month distribution of time of maximum wind (PST) at the Fort Ord profiler site April-September 1992 (from Round, 1993)

category at 16 percent and the double surge accounted for approximately 7 percent No sea breeze and unclassifiable days account for the remaining 12 percent of the days.

The most common time of maximum wind occurs at 1330 PST (Refer to Figure 3.5). The primary range of occurrence for this phenomenon covers the hours 1300 to 1600 PST. This range is skewed to the right indicating the dominance of later rather than earlier times. Maximum winds occurring earlier than 1230 or after 1630 PST are infrequent.

Time of sea-breeze onset is determined from daily station records of wind speed and direction, temperature, dew-point, pressure, incoming shortwave radiation and incident longwave radiation. The most likely time of sea-breeze onset is between 0830 and 1100 PST with the most frequent time being 1000 PST (Refer to Figure 3.6). This distribution is skewed earlier than 1000 PST. Onsets later than 1100 are uncommon.

F. INTRIERI ET AL. LASBEX PRELIMINARY RESULTS

The Land-Sea Breeze Experiment (LASBEX) conducted in Monterey Bay from 15 September to 30 September 1987 focused on the characteristics of central California's sea-breeze circulation. The experiment collected data using numerous meteorological sensing systems, which included a Doppler acoustic sounder (SODAR), a Doppler lidar, rawinsondes, surface meteorological systems and satellites. Intrieri et al. (1990) discusses some preliminary analysis of this data that is useful in this thesis investigation. Their study examined data from the NOAA lidar on 16 September 1987. On this day in the early morning, a mature, 1000 meter deep land breeze was blowing steadily from the east at 7 m/s A sea-breeze started in the lowest surface layer moving at 1-2 m/s The lidar first

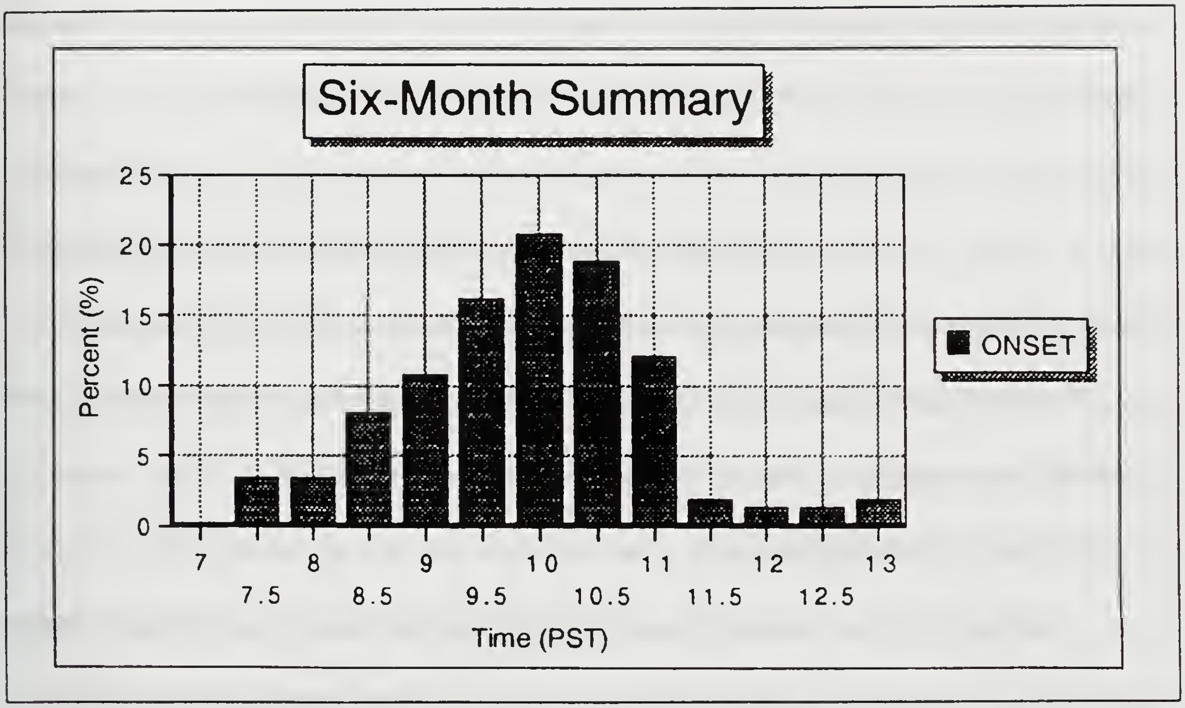

FIGURE 3.6 Six-month distribution of time of onset (PST) at the Fort Ord profiler site April-September 1992 (from Round, 1993)

detected the onshore flow at 0920 PST. On top of this shallow sea breeze, the land breeze remained virtually unaffected. Within four hours of its initiation, the sea breeze reached its maximum depth of 1000 meters and wind speed of 8 m/s. On this particular day, the study concluded that the sea breeze and land breeze were comparable in depth, speed, and height of maximum speed. Most notable differences were in the initiation characteristics. The sea breeze was more abrupt upon onset than the land breeze. The sea breeze developed in the lowest surface layer then gained speed and height as the day progressed. On the 14 days of measurements during this study, the return flow was not clearly defined on any of the days. The researchers observed when there was a light return flow layer above the sea breeze it seems to be more of a remnant of the previous nights land breeze than a true compensatory current. On most of the study days, the flow aloft was from a westerly direction similar to that of the sea breeze. Finally the study noted the direction of the sea breeze near the coast varied from northwest in some days to west or southwest on others.

G. YETTER'S LINEAR MODEL

Yetter (1990) used data from the LASBEX study to develop a simple linear model that investigated the speed and direction of the sea-breeze front. This model determined that the mean direction of sea-breeze frontal propagation in Monterey Bay was east to southeast at 125°± 26°. For a straight, level coastline the theoretical propagation direction of the sea-breeze front would be eastward. The propagation direction of 125 ° implies a tendency for the sea breeze to propagate down the Salinas Valley, which is orientated at roughly 140 °. The study also noted the acceleration of the sea-breeze front once it entered the Salinas Valley. Since both the up- valley and sea-breeze circulations are directed into the valley, the additive effect is to increase the speed of propagation of the sea-breeze front. Overall the speed of the sea-breeze front was variable, ranging from 1 m/s to about 3 m/s, with a mean speed of advance of 2 m/s ± .54 m/s. Normally wind vectors would show a clockwise turning with time, however the LASBEX data sets showed a counterclockwise turning of the wind. Yetter (1990) explains this by suggesting that the sea breeze is superimposed upon the monsoonal flow, which hinders the offshore flow usually expected in the early morning. Finally, the study concludes there was evidence of a second inland penetration of marine air on 16 September and that further research into this phenomena is recommended.

H. FAGAN'S ANALYSIS USING SODAR AND LIDAR

Another study using the LASBEX data was done by Fagan (1988). By using sodar, which utilizes the backscatter of acoustic energy to determine certain parameters in the atmosphere, and lidar, which utilizes a laser beam to emit pulses of high intensity light that will be reflected from gases, aerosols and particulates, Fagan (1988) hoped to obtain a comprehensive view of the sea/land-breeze intensity and structure in Monterey Bay.

Fagan (1988) determined the average onset time for the sea-breeze to be 0942 PST. The earliest onset time was 0844 PST and the latest was at 1030 PST. Wind speeds of the sea breeze reached maximum intensity about the same time as maximum height was achieved. The maximum speeds ranged between 6 m/s and 10 m/s. Offshore flow was clearly present before the onset of the sea breeze. This flow was considered the established land breeze and was usually confined below 400 meters. Once the sea breeze became established, it increased until it assumed a relatively constant elevation. Above this level, the return flow which completes the sea-breeze circulation was detectable by the sodar. Since the sodar signal had little data past 750 meters, the extent and characteristics of the return flow could not be determined. However, the information from the lidar clearly showed offshore flow on 16 September 1987 that began around 400 meters and extended vertically up to 1600 meters. Thus the depth of the offshore flow detected by the lidar was over twice as large as the onshore flow, which is the typical dimension seen in other studies. Nevertheless, the speeds in this offshore flow are either equal or larger than the onshore flow. This observation contradicts previous studies which noted that the speed of the offshore flow was roughly half the magnitude of the onshore flow.

In measuring the direction of the sea-breeze front propagation, Fagan (1988) achieved similar results reached by Yetter (1990) in Monterey Bay. Fagan found the average of sea-breeze fronts to propagate in a direction 150° ± 20°, which is down the Salinas Valley. It was also observed that the sea breezes advanced onto land with a mean speed of 2.54 m/s and lasted between 8 and 13 hours. The maximum vertical extent of the sea breeze was determined for the 10 cases in September of 1987. The sea breeze had a mean elevation of 659 meters, and ranged between 570 and 800 meters. Fagan (1988) concluded by doing a case study for 16 September 1987, for it was on this day that both the lidar and sodar detected the passage of two sea-breeze fronts. Because the sodar had limited data above 750 meters and the lidar beam is strongly attenuated by clouds and fog, Fagan's (1988) study was somewhat limited by technical capability.

I. BANTA ET AL. PULSED DOPPLER LIDAR

In attaining the picture of central California's sea breeze, Banta et al. (1993) relied mostly on the data from the Wave Propagation Laboratory's Doppler lidar. The lidar data was shown to be consistent with observations from other systems such as sodar and more conventional in situ measurements. In order to obtain the best defined sea breeze, the study focused on days in which there was an offshore ambient wind flow. The results of the study concluded that the Monterey Bay sea breeze is similar to the sea breeze observed in other coastal areas. Specifically, all data showed a sensitivity of sea-breeze structure to ambient wind direction. Two major topographical effects were observed. First, the westerly onshore flow grew faster over land than over water, this was probably due to enhancement from the slope flow. Data revealed that upslope westerly flow toward the mountain ranges to the east apparently preceded the advent of the sea breeze near the coast areas. The slope flow therefore aided in the land growth of the Monterey Bay sea breeze. Secondly, as westerly sea breeze flow was established over most of the region within 20 km of the coast, southeasterly, down-valley flow persisted for up to 1 hour in the Salinas River Valley because of the inertia of that along-valley flow system. Hence the lidar was observing during this late morning hours was the continuation of the night-time down-valley flow. Banta et al. (1993) have also suggested that the complex inland terrain may have contributed to the absence of a compensatory return flow from land to sea over the coast. These slope and valley circulations are postulated to absorb the mass divergence aloft, which existed above the low-level convergence at the sea-breeze front. This absorption would explain why it would not be necessary for mass compensation to occur locally within the sea-breeze system

Unlike many studies that have observed significant Coriolis turning of the winds through the daytime hours, Banta et al. (1993) found no consistent tendency for the sea-breeze flow to turn northerly through the afternoon hours. Since both return flow and Coriolis deflection is absent in this study, Banta et al. (1993) agree with Atkinson's (1981) argument that Coriolis turning only occurs when air parcels are recycled for several hours within the same sea-breeze circulation cell. Because the sea breeze has no return flow, there is no recycling and no Coriolis effect.

An intriguing incident detected on 27 September was the transient sea-breeze precursor or as commonly referred to as the "minor sea breeze". It is produced by the temperature contrast between the beach and the adjacent waters, and it precedes the onset of the normal or major sea breeze. On this day the sea-breeze precursor circulation is 5.5 km wide and a little less than 50 m deep. At 0842 PST, this feature disappears and the flow returns to the offshore flow from the surface to a height of ~ 1 km. This minor sea breeze extended only over a small area and was short lived. By 1200 PST, a mature sea breeze was established, extending upward at least 1 km from the surface. As the sea-breeze layer deepened during the afternoon, it extended upward into the stable inversion layer. This study demonstrated that a complex coastal terrain such as the one we have in Monterey can clearly alter the more canonical sea-breeze scenario. These differences further explain why observations in this region compare poorly with predictions from analytical models. These models do not include the many complicated effects that occur along the Monterey Bay coastline in their idealized model formulations.

IV. REMOTE SENSING EQUIPMENT

A. HOW A 915-MHZ WIND PROFILER WORKS

With the need to improve the accuracy of weather forecasting, meteorologists have demanded increased reliability upon observational techniques. Unfortunately, many current in-situ and remote sensing systems are inadequate to meet these more exacting demands. For example, radiosondes are usually only deployed on a schedule of one launch every six to twelve hours, which often falls short of the time scale of observations needed to study and understand mesoscale weather phenomena. Additionally, other remote sensing systems such as lidar are limited in the marine environment because of strong attenuation by cloud droplets and fog. Sodar is limited by the height of reliable data returns. This limitation was experienced by researchers in the LASBEX experiment who encountered sodar's 750 meter height limit. More recent technological advances have proved the value of radar wind profilers. Equipped with remote upper-air wind observing capabilities and the ability to attain unsurpassed detailed measurements of synoptic scale and mesoscale wind fields have made the profilers very beneficial in investigating atmospheric phenomena (Nieman et al. 1992).

The wind profiler used in this thesis is a 915-MHz Doppler Radio Detection and Ranging instrument developed by Radian Corporation. Its commercial name is LAP-3000, which stands for Lower Atmospheric Profiler. The 3000 indicates its vertical range is approximately 3000 meters. This wind profiler is an atmospheric remote sensing instrument that gives information about a volume of the atmosphere without being physically located in that volume. The radar transmits a pulse of electromagnetic (EM) energy in a specific direction. When the pulse encounters a "target," EM energy is scattered. A small detectable amount of this energy returns to the radar, which computes the distance to the target using the time delay from the initial pulse to the return backscattered energy (Refer to Figure 4.1). The targets are actually refractive irregularities in the atmosphere. They are formed due to the wind and uneven heating of the earth's surface. These motions cause variations in temperature, humidity, and pressure over relatively short distances. These variations finally breakup into smaller and smaller eddies, which become the refracture irregularities or "targets" for the wind profiler. The major advantage over more conventional radar systems is that the wind profiler can obtain returns in clear air regimes from these almost imperceptible irregularities.

To avoid getting into too much detail that would exceed the scope of this thesis, only basic parameters will be reviewed in examining the 915 MHz wind profiler. The manual published by the Radian Corporation (1994) provides a brief but informative analysis of the LAP-3000. The generic name "profiler" comes from the radar's ability to display data for many heights of the atmosphere simultaneously, thus giving a profile of the atmosphere. As discussed earlier, the profiler computes height by using the time delay between the outgoing transmitted pulse and the return echo; however, wind speed and direction are determined by using the Doppler principle. Behind the Doppler principle and its application to the wind profiler is the precept that by tracking refractive irregularities carried by the wind, information is revealed about the wind. Wind profilers make

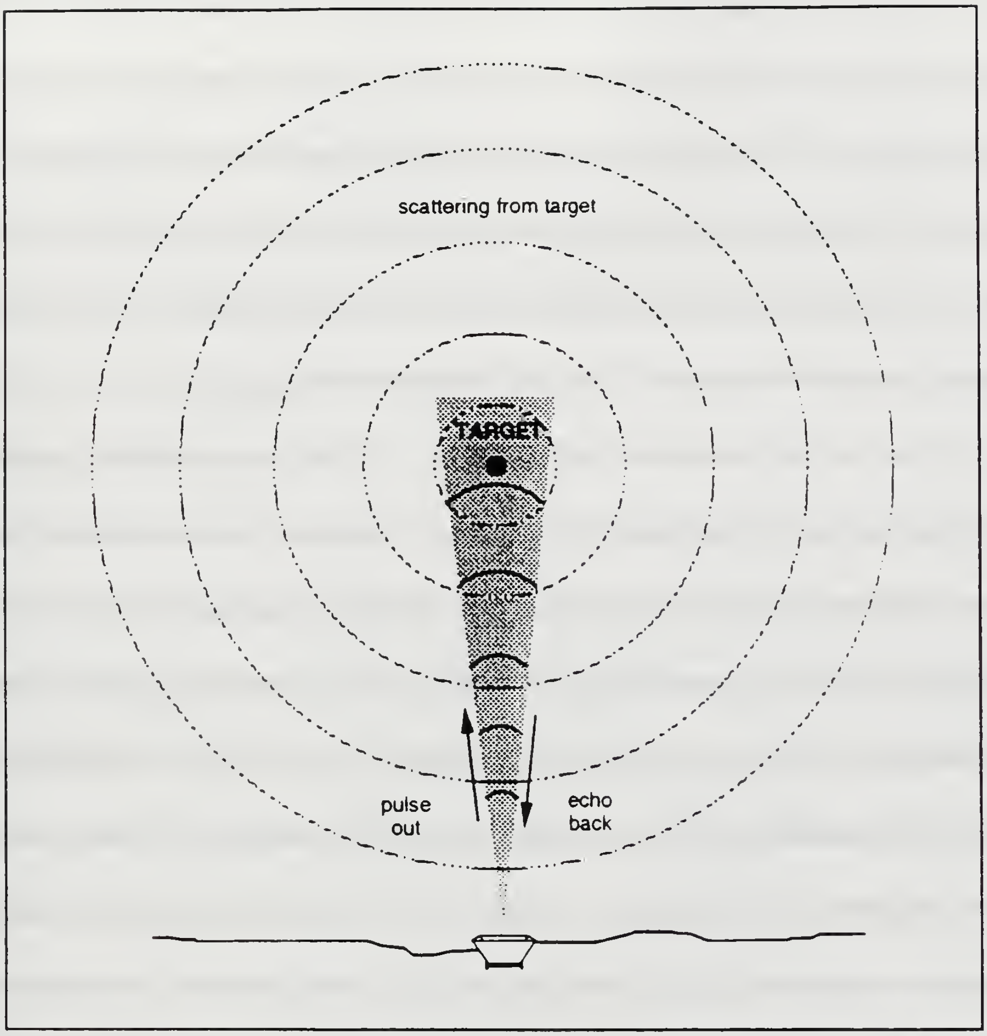

FIGURE 4.1 Diagram of transmitted electromagnetic energy returning to the wind profiler after being backscattered by a target (from Radian Corp. *Training Guide for the LAP-3000,* 1994 with permission).

measurements in as many as five directions in order to compute both wind speed and direction One beam is directed vertically while the other four are tilted about 21 ° from the vertical and directed in the four orthogonal directions. This received data then goes through a signal processing stage that uses Fast Fourier Transform (FFT) and a windowing technique to remove anomalies such as ground clutter. Some backscatter is returning to the profiler even before it has stopped transmitting the electromagnetic pulse and prepared itself for receiving. This will cause undesirable data at the surface. To provide reliable surface level returns in this thesis, surface data from ground based meteorological stations were incorporated at each of the four sites into the monthly profiles.

The minimum and maximum height coverage of a profiler is dependent upon several factors. Three factors that cannot be controlled by the operator are: wavelength of the radar, size of the antenna, and transmitted power. However, the operator can control the pulse duration and inter-pulse period (IPP). By decreasing the pulse length, the operator can achieve improved range resolution at the expense of vertical range. If the IPP is too short it will detrimentally affect the system performance by increasing the likelihood of interference between successive pulses. Operators must compromise among the desired characteristics i.e. low and high height coverage versus range resolution in order to achieve data required for a specific purpose.

B. HOW A RADIO ACOUSTICS SOUNDING SYSTEM (RASS) WORKS

The Radio Acoustics Sounding System (RASS) is an option that can be added to the wind profiler to provide profiles of virtual temperature data. The RASS system is typically composed of four high-powered 2-KHz acoustic sources distributed around the radar

Refer to Figure 4.2 to gain a better understanding of the proximity of the co-located wind profiler and RASS systems. By measuring the velocity of acoustic wavefronts using Doppler radar, RASS can determine the speed of sound **c**. Once the speed of sound is known, virtual temperature can be found to a very good approximation using the relationship **Tv = (c/20.047)^2** (May et al. 1990). An important feature of the RASS is its ability to measure virtual temperature profiles with the same vertical and temporal sampling resolution as its co-located wind profiler (Nieman et al. 1992). As discussed above, the RASS has the same minimum height coverage and range resolution as the profiler; however, the maximum height limit is typically only 1-2 kilometers due to the atmospheric absorption of the acoustic waves.

As demonstrated by May and Wilczak (1993) in their RASS study in Denver; warm, moist environmental conditions typical of the summertime lead to better height coverage. This is because acoustic attenuation is a distinct function of temperature and humidity. Higher temperature and humidity levels propagate acoustic signals with less attenuation then colder or less moist regions; furthermore, RASS is strongly dependent on the profiler wavelength. Profilers operating at lower frequencies allow the RASS to measure temperatures to considerably greater altitudes (May et al. 1988). A higher frequency profiler requires the RASS to use higher frequencies and the resulting acoustic attenuation increases dramatically with this increase in frequency. The wind profiler also dominates the largest portion of the averaging period in attaining its velocity measurements. RASS uses the remaining time period to obtain vertical temperature data. A common arrangement is to transmit 50 minutes in the wind mode and 10 minutes in the RASS mode for every hour

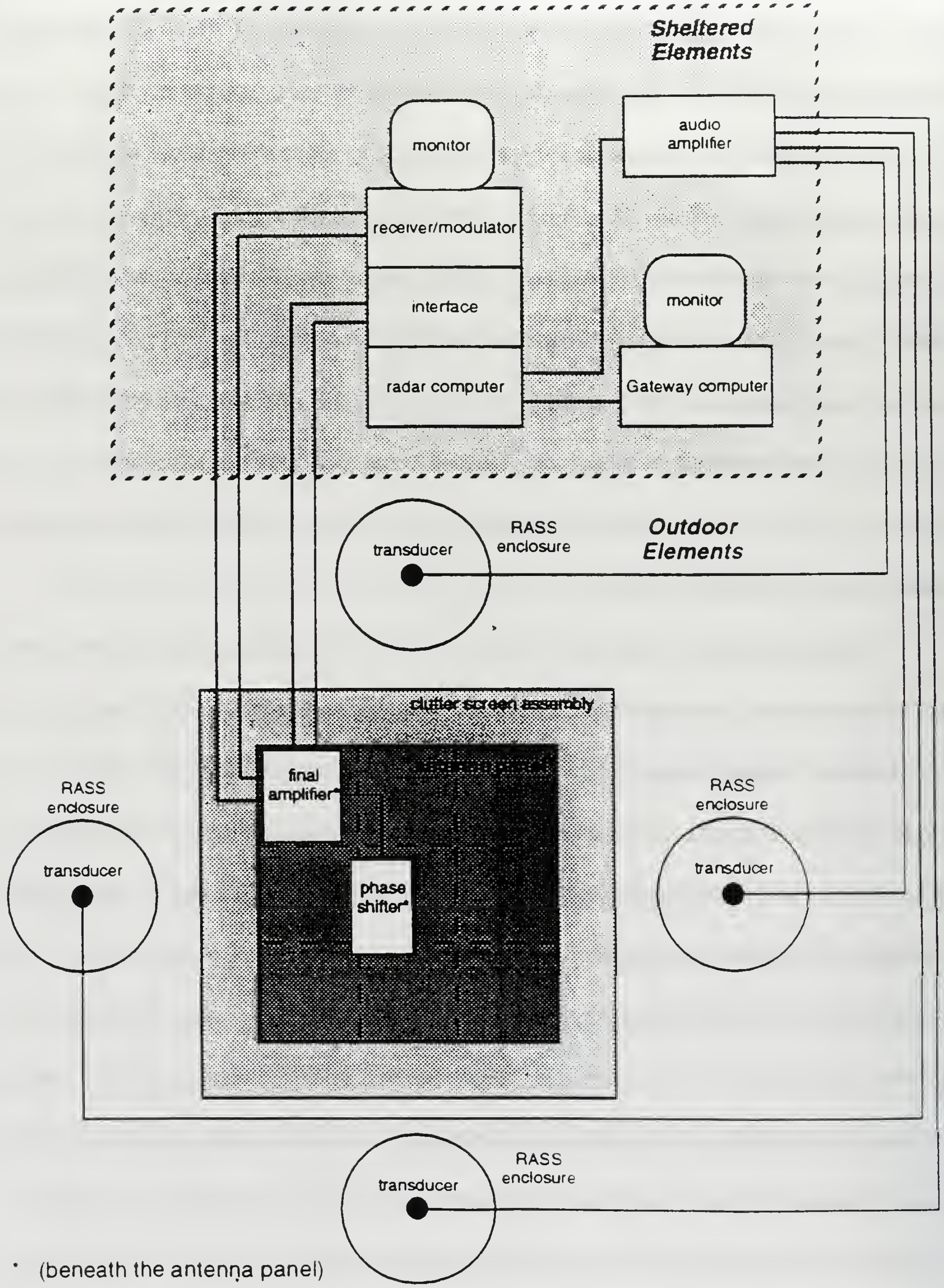

FIGURE 4.2 Diagram displays the location of the RASS transducers in relation to the radar wind profiler when its added as an option Additionally, the diagram depicts which equipment is sheltere and which equipment remains unprotected from the elements (from Radian Corp . *Training Guide f the LAP-3000,* 1994 with permission)

of operation (Radian Corp. 1994).

C. ATMOSPHERIC EFFECTS ON PROFILER PERFORMANCE

Since both the wind profiler and the RASS system measure refractive irregularities in the atmosphere any changing atmospheric conditions can dramatically affect the performance of both pieces of equipment. Reduced height range and large "holes" in data are usually the result of changing atmospheric conditions. The conditions that affect the performance of the wind profiler and RASS system are as follows: humidity, turbulence, precipitation, high winds, and temperature. The (Radian Corp. 1994) Training Guide provides a comprehensive review of these conditions.

1. Humidity

The higher the humidity or amount of moisture in the air the better the profiler works. This is because moist air has larger refractive index variations to backscatter interrogating EM and acoustic wavefronts. If the air is dry, holes in the data may result. Consequently wind profilers are best suited for marine environments where the extra moisture is available. In high latitude cold regions, the profilers perform poorly due to numerous "holes" in the data returns. Understandably, the RASS system performs well in an atmospheric region with high humidity as there will be much less attenuation of the transmitted acoustic wave.

2. Turbulence

The more turbulence there is in the atmosphere, particularly turbulence with a scale of one-half the profiler wavelength, the better the profiler works. Increased turbulence, whether thermally or topographically induced, results in more irregularities to reflect the profiler's signals. More reflections that occur in a volume of air will result in better profiler data. Conversely, higher turbulence is not particularly beneficial to the performance of the RASS system. Turbulence can disrupt the coherence of the acoustic wavefront used for temperature measurement and thus reduce the range obtained.

3. Precipitation

Most types of precipitation such as rain, snow, and hail can have detrimental effects upon the profiler. Since precipitation particles return stronger signals than clear air, the radar will track the particles rather than the wind component. When the precipitation moves in a different direction from the air around it, the profiler will misinterpret that direction as the true wind direction. This typically happens more often with precipitation moving vertically than the horizontal components. Temperature measurements from RASS are not usually possible during times of precipitation because of the impact on the vertical wind velocity component, thus erroneous data are produced.

4. High winds

High winds have a detrimental affect for both the profiler and the RASS system. Clutter signals from objects such as trees and power lines can exhibit enough of a Doppler signal to overwhelm the system's ability to screen that out during high wind times. Increasing ground clutter can create incorrect vertical velocities used for temperature correction, as well as reducing the range of the RASS by displacing the acoustic signal away from the radar beam.

5. Temperature

The RASS system is much more affected by temperature than the profiler. Sound waves travel at different speeds for varying temperatures as was discussed earlier. Cold dry air exhibits the highest attenuation. Very cold or warm air propagates acoustic signals better resulting in improved range for virtual temperature measurements.

D. COMPARISONS OF THE WIND PROFILER WITH MORE CONVENTIONAL METHODS

Many comparisons have been conducted over the last two decades to determine the relative accuracy of the wind profilers. Using conventional in situ instruments such as aircraft, balloon launched radiosondes, and, rawinsondes; researchers conducted numerous studies under varying conditions in attempts to find any significant differences. The wind profiler being a remote sensing instrument gives information about a volume of the atmosphere at a distance without being physically located in the volume. In contrast, in situ instruments give information about a specific point in the atmosphere. These differences make comparisons somewhat difficult.

May et al., (1989) did a comparison of RASS data from Denver's Stapleton International Airport. Using 50 radiosonde ascents, the root mean square (rms) differences were 1° C when compared with the RASS data. This rms difference is considered very good since simultaneously launched radiosondes show similar rms differences. Fukao et al., (1982) studied winds obtained with the Arecibo 430 MHz radar on twenty-six different days and concluded that most of the differences between the radar and balloons measurements in the lower troposphere can be explained by experimental errors, particularly those in the rawinsonde measurements. Further conclusion was that the 430-MHz as well as the 50-MHz Doppler radar measurements of winds provide more accurate and more frequent wind profiles than conventional rawinsondes. Additionally, radars can measure the vertical velocities; thus, providing important supplemental data to the indirect method that is typically used to derive the vertical velocity from radiosonde data. The radar observations also allow gravity wave fluctuations ("geophysical noise") to be integrated out; radiosonde observations do not.

Balsley et al., (1988) investigated the capability of a 50-MHz radar wind profiler located in the tropical Pacific to accurately determine long-period average vertical wind profiles in the troposphere and lower stratosphere in both the clear atmosphere as well in convective activity. Working on the Island of Pohnpei, the researchers compared the vertical wind profiles obtained from the wind profiler. and vertical wind profiles obtained earlier by more conventional methods using appropriately situated rawinsonde sites. The comparison showed that, while the general features of the profiles obtained by both techniques are similar, the profiler results exhibit somewhat more detail. It was concluded that an agreement on the scale of a fraction of a cm/s under quiet conditions is attainable. Moreover, the wind profiler provided additional features in the profiles not obtained by other techniques. For example, profiler results show that the weak subsidence observed during clear periods is not limited to heights below the tropopause, but rather appears to extend well into the lower stratosphere.

Since radiosondes have been the de facto standard by historical precedence, its seems logical that many studies have compared them with new technology such as wind profilers. Unfortunately, these studies may have not made a large number of comparisons occurring over many months or years. In order to obtain some long term associations, Weber and Wuertz (1990) made extensive comparisons of measurements obtained with a UHF 915-MHz wind profiler; operated by Wave Propagation Laboratory WPL, and rawinsonde observations taken by the National Weather Service NWS both located at the Stapleton International Airport in Denver, Colorado. Measurements were obtained and comparisons were made twice daily at the times of the radiosondes ascents from mid-January 1984 through October 1985. Since rawinsonde ascents take up to an hour, many kilometers are covered laterally, therefore measurements are made at different heights and different location when compared to the profiler. Good agreement is expected between rawinsondes and the wind profiler in cases of uniform winds. However, when winds are changing rapidly over an hour, one does not expect good agreement. In doing 17,799 comparisons over a two year period, the study discovered the differences in the horizontal wind component had a standard deviation of only about 2.5 m/s. This standard deviation is so small that it is not much different from the built in instrument error of either the rawinsonde or the wind profiler. Strauch et al., (1987) found a standard deviation of about 1.3 m/s in clear air and Wuertz et al., (1988) found a standard deviation of about 2-4 m/s in precipitation just for UHF wind profiler measurements.

To do the statistical comparisons objectively, (Weber and Wuertz 1990) included all measurements taken during the time period, regardless of conditions. However, since some comparisons would include cases when the two instruments would be measuring different winds because of meteorological variability. Large disagreements would occur These anomalies were defined as any differences between the **u** or **v** component measurements exceeding ± 15 m/s. Using this criterion only about 2 percent or 374 pairs of data were edited from the original 18,173 measurement pairs. Figure (4.3) includes a side by side comparison of the wind profiler and NWS rawinsonde for 12 June 1984. The data shows very good agreement. Considering that this study used data over nearly two years, covering all seasons, and including a wide range of climatic conditions; a standard deviation of about 2.5 m/s between the wind profiler and the rawinsonde proves that rawinsonde and wind profilers give comparable wind component measurements. The results of this study suggest that differences are mainly due to meteorological noise. A new network of wind profilers should reduce this noise level with improved signal-to-noise ratios and with improved data sampling that is continuous over time.

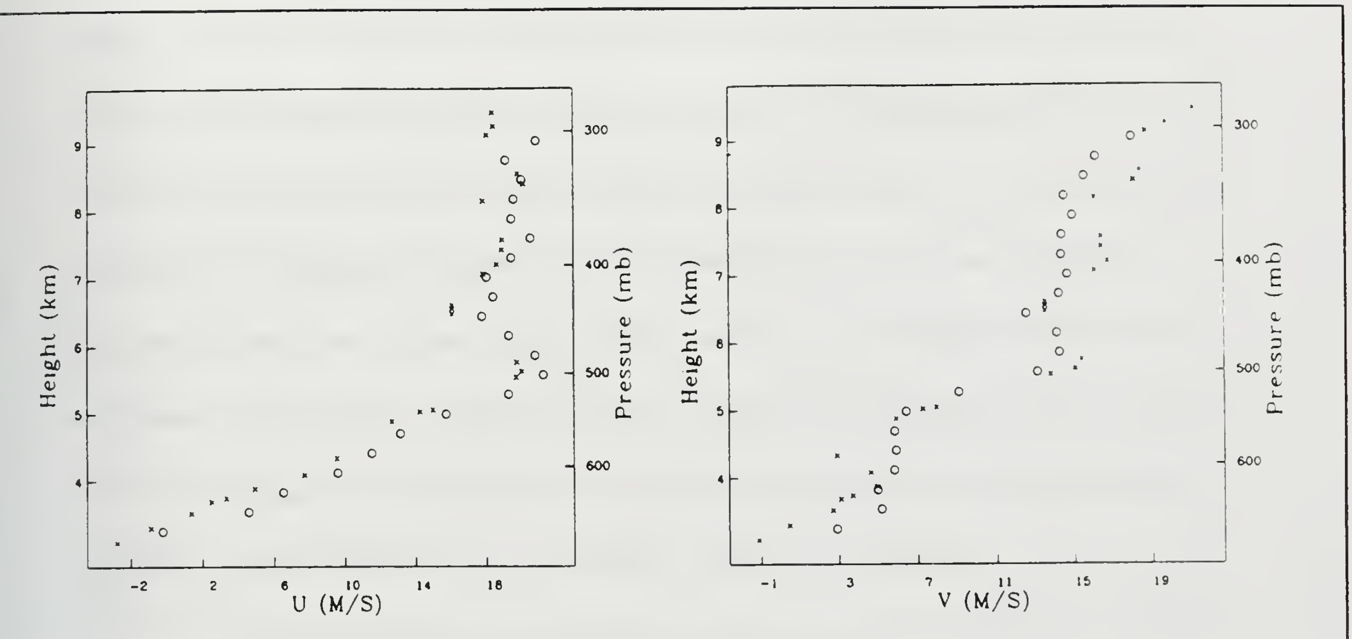

FIGURE 4.3 The general agreement in Figure (4.3) between the wind profiler (O's) and the rawinsonde (X's) in Denver Colorado at 1200 UTC on 12 June 1984 is commendable. Although some systemic differences appear that do not seem to be caused by errors in either instrument's measurements. For example, there is a 1-3 m/s bias in the **v** component at the upper levels. This could be due to the large spatial separation of the two instruments at those levels where each is measuring different winds. Differences at the lower levels, though, are probably due to the way each instrument samples over space and time (from Weber and Wuertz, 1990).

V. DATA DESCRIPTION

A measurement program was executed during June-August 1994 in the Monterey Bay area to better understand the structure of the sea/land breeze. This program was part of the Real-time Environmental Information Network and Analysis System (REINAS) Project. The goal of this project, which is supported by meteorological and oceanographic scientists in the Monterey Bay region, was to provide an environmental database to advance both real-time and retrospective regional scale environmental science. In attempts to better understand the relationship between the diurnal thermally-driven circulations and the dominant synoptic flow, remote sensing stations were set up in strategic locations during the summer months of 1994. These location are: Santa Cruz, Hollister, Point Sur, and Fort Ord. Each of these locations should provide different data applicable to their individual topography and proximity to the bay and ocean (Figures 3.2 and 3.3).

In Santa Cruz, a 915-MHz wind profiler was set up at Long's Marine Lab, which is about 2 miles west of the city's pier. The wind profiler was at an elevation of 12 m and located at 39.95°N and 122.07°W. This is the only location that did not have the RASS system operating. Santa Cruz is also located in the warmest part of the Bay, protected from the northwest synoptic flow by the Santa Cruz mountains.

Further to the east, approximately 30 km inland, lies the town of Hollister. Another 915-MHz wind profiler and co-located RASS system was positioned in a farmer's field. This system was at an elevation of 55 m and located at 36.92°N and 121.40°W. Some marine air invasion should be detected at this site since it lies in a gap between the Santa

Cruz mountains and the Gabilian Range. Diurnal modulation due to sea breeze activity is expected to occur later and to a lesser extent at this location.

The third location is the only permanent positioned 915-MHz wind profiler. The Fort Ord profiler and RASS system is located at the former Fritsche field now the Marina Municipal Airport. Away from the landing strip, this system is at an elevation of 51 m and located at 36.69°N and 121.76°W. This location is approximately 4 km from the Bay and located at the mouth of the Salinas Valley. This valley is the distinguishing topographical feature in the Monterey Bay region. Many previous studies such as LASBEX have observed a clockwise turning of the winds as they enter this valley. This thesis will investigate the synoptic/mesoscale wind interactions in this location.

Point Sur is the final location of this project. Initially, the 915-MHz wind profiler and RASS system were to be positioned adjacent to the lighthouse on the Point Sur Rock. However, the gusting winds were too strong so researchers set up the equipment at the nearby Point Sur Naval Station. A low-level spit provided the system with an elevation of 10 m at the location of 36.31°N and 121.90°W. This station will provide the data to investigate the channeling effects and blocking of a topographical barrier. Mountains exceeding 500 m at the shoreline may prevent any mesoscale sea/land breeze from forming. Vertical profiles from this station should provide some interesting results to better understand the coastal mountain topographical effects on local wind flow.

VI. ANALYSIS OF THE DATA

A. OVERVIEW

Coastal sea breeze behavior is studied using monthly averages for the four profiler sites positioned around Monterey Bay. The data from the summer months of June, July, and August 1994 have both wind and virtual temperature measurements from the RASS system at three of the profiler sites. In order to conveniently compare the four profiler sites in this study, a common virtual temperature scale is incorporated to account for the coldest and warmest temperatures. As expected, the inland Hollister site recorded the lowest monthly temperature of 10.1°C and the highest monthly temperature of 28.7°C. Fort Ord's site has 60 m vertical resolution radar returns while the other sites have 100 m resolution. All sites have consistent vertical coverage to 1500 m except Point Sur where maximum vertical range was limited to 1000 m. By examining each site individually and then making comparisons among the other sites, factors influencing the mesoscale sea breeze in the central California region are described. Additionally, averages of all three months will address summer characteristics of each location.

B. FORT ORD PROFILER SITE

1. Winds

The average winds and temperatures for the month of June 1994 at the Fort Ord profiler site are presented by Figure (6.1). The average wind data define the diurnal sea breeze at the surface as well as aloft. Surface data shows a strengthening of the winds beginning near 0900 PST with an afternoon maximum of 14 kts (7 m/s) between 1100 and

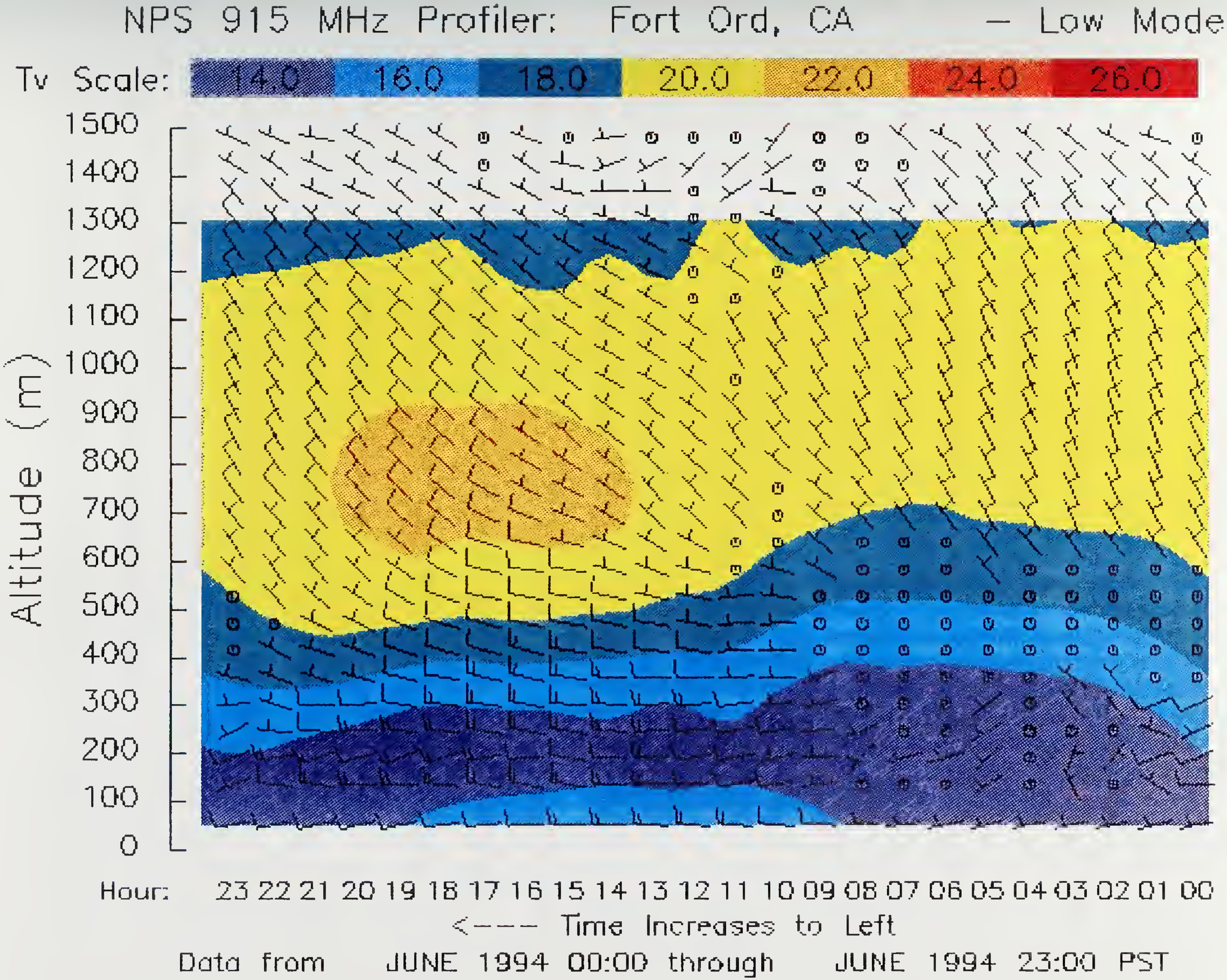

FIGURE 6.1 915-MHz wind profiler averages for 1-30 June 1994 at Fort Ord, CA. The data returns have 60 meter resolution.

1500 PST. This agrees with Round's (1993) results for the Fort Ord site, which found the most likely time of sea-breeze onset to be at 0900 PST (Refer to Figure 3.6). Round (1993) also found that the most common time of maximum winds occurs at 1330 PST with an average maximum windspeed of 8 m/s. This June 1994 data set is consistent with those results. During the evening, average surface winds drop to 5 kts by midnight but remain westerly. There is no mean land breeze in the average data.

The region of strong surface afternoon winds extends vertically from the surface to 400 m. The peak in the average wind is 16 kts at 300 m occurring at 1500 PST. The maximum winds above the surface layer start and extend later than at the surface. At 300 m, the 15 kts winds start 1300 and continue to 2000 PST. In the late afternoon and evening, these stronger winds continue even though surface winds are decreasing. At night the winds between surface and 600 m are calm or light and variable.

The large scale prevailing wind direction in June is northwesterly. The westerly surface and near surface winds are likely due to sea-breeze flow perpendicular to the coast as well as the inland heating in the Salinas and other valleys. Recall local topography in Figure (3.3). Foster (1993) found surface winds at Monterey, Fort Ord, and Santa Cruz all turned westerly as the sea breeze grew in scale.

Above 500 m evidence of the large-scale continental sea breeze is found. In the synoptic flow between 600 and 900 m the hourly average winds are backing 20° to 30° to a more westerly direction during the afternoon and become more northerly at night. The magnitude of this 500-1200 m continental sea-breeze circulation is approximately 1 m/s. Figure (6.2) depicts the mean and anomalous winds at 700 m for the monthly average in

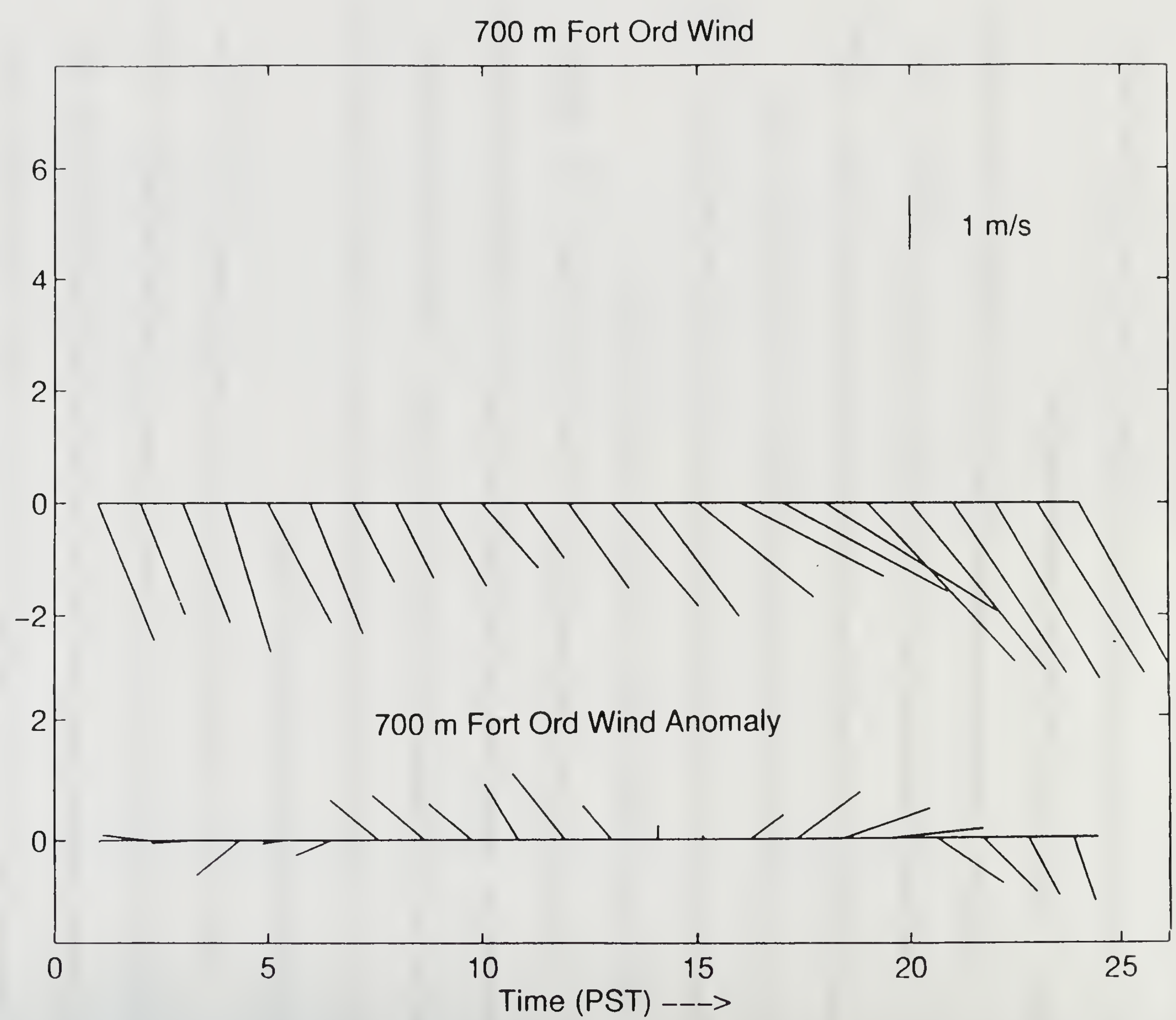

FIGURE 6.2 The mean and anomalous winds at 700 m for the month of June 94 at the Fort Ord profiler site. Anomalous winds show clockwise turning throughout the 24 h period

June at the Fort Ord site. By subtracting out the mean prevailing northwest winds, clear evidence of clockwise turning occurs throughout the day in the anomalous winds plot. Offshore flow dominates prior to 1000 PST when winds turn onshore for the rest of the day. Above 1000 m, the June average winds during the day are from the same prevailing northwest direction but are somewhat stronger during the night (> 10 kts) and weaker during the morning and early afternoon.

The wind pattern during July at Fort Ord is similar to winds of June (Refer to Figure 6.3). July's sea-breeze onset time is earlier occurring at 0800 PST. The strong afternoon winds average 15 kts and extend to 400 m, however the time period of high winds is less. In upper levels (600-1200 m), the winds begin backing earlier than in June starting at approximately 1000 PST. The large-scale continental sea breeze is clearly depicted in the July data. A magnitude of 1 m/s for onshore flow and offshore flow is similar to June.

Figure (6.4) describes the average winds for August 1994. August also has maximum surface winds of 15 kts between 1200 until 1400 PST. The month of August had the latest sea-breeze onset time at 1000 PST. August's wind pattern is more similar to the month of June than July in that August's strong winds in the sea-breeze circulation maintain speeds above 15 kts at 100 m beyond 1800 PST while experiencing decaying winds at the surface. Aloft, the northwest winds aloft begin backing to a westerly direction at 1000 PST This is the same time backing aloft also occurs in the month of June. The large-scale continental sea breeze is present in the August data but is less distinct than in June and July.

Evidence of any compensatory return flow was not detectable during any of the three summer months in Fort Ord. Historically, the depth of the return flow is usually twice

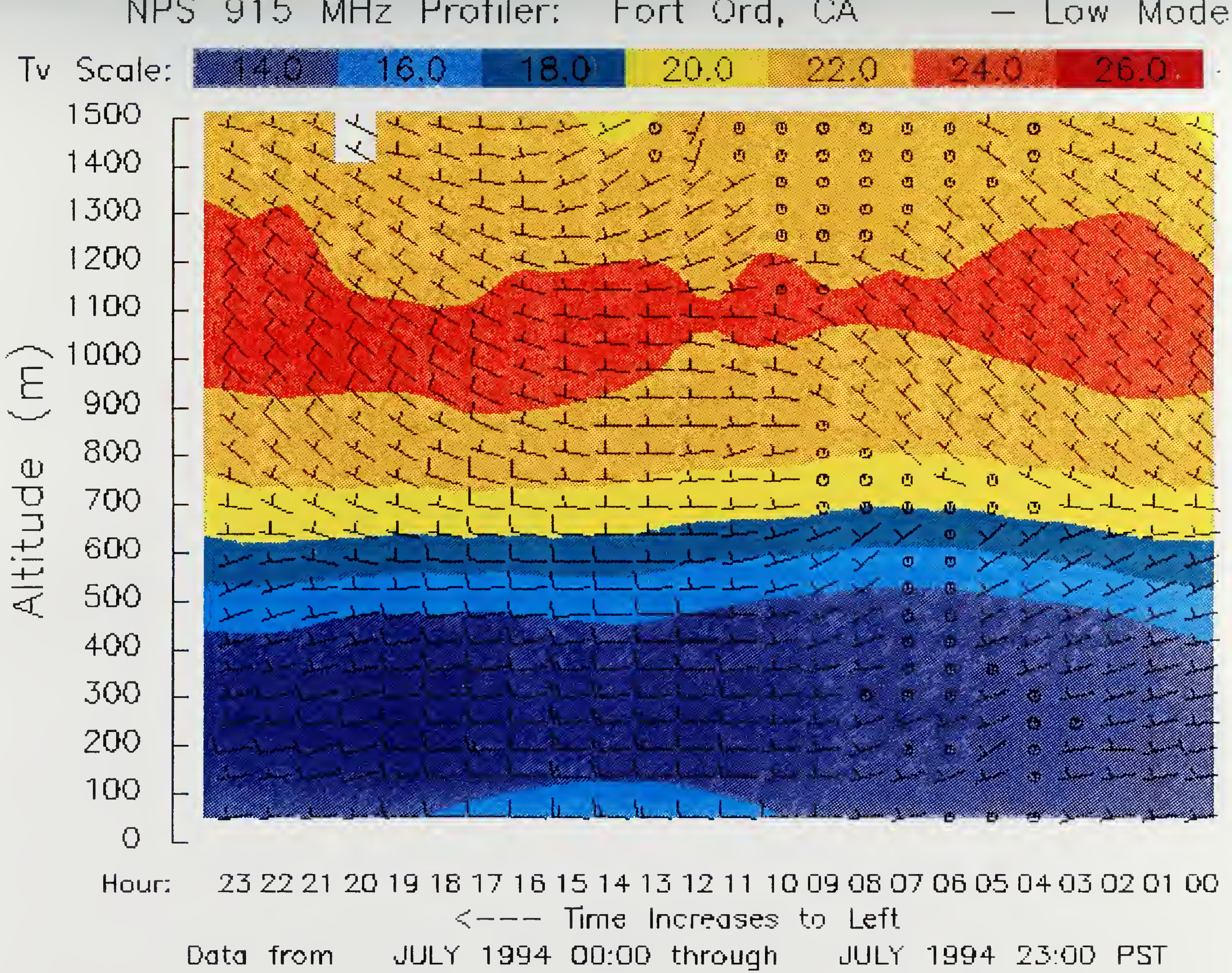

FIGURE 6.3 915-MHz wind profiler averages for 1-31 July 1994 at Fort Ord, CA. The data returns have 60 meter resolution.

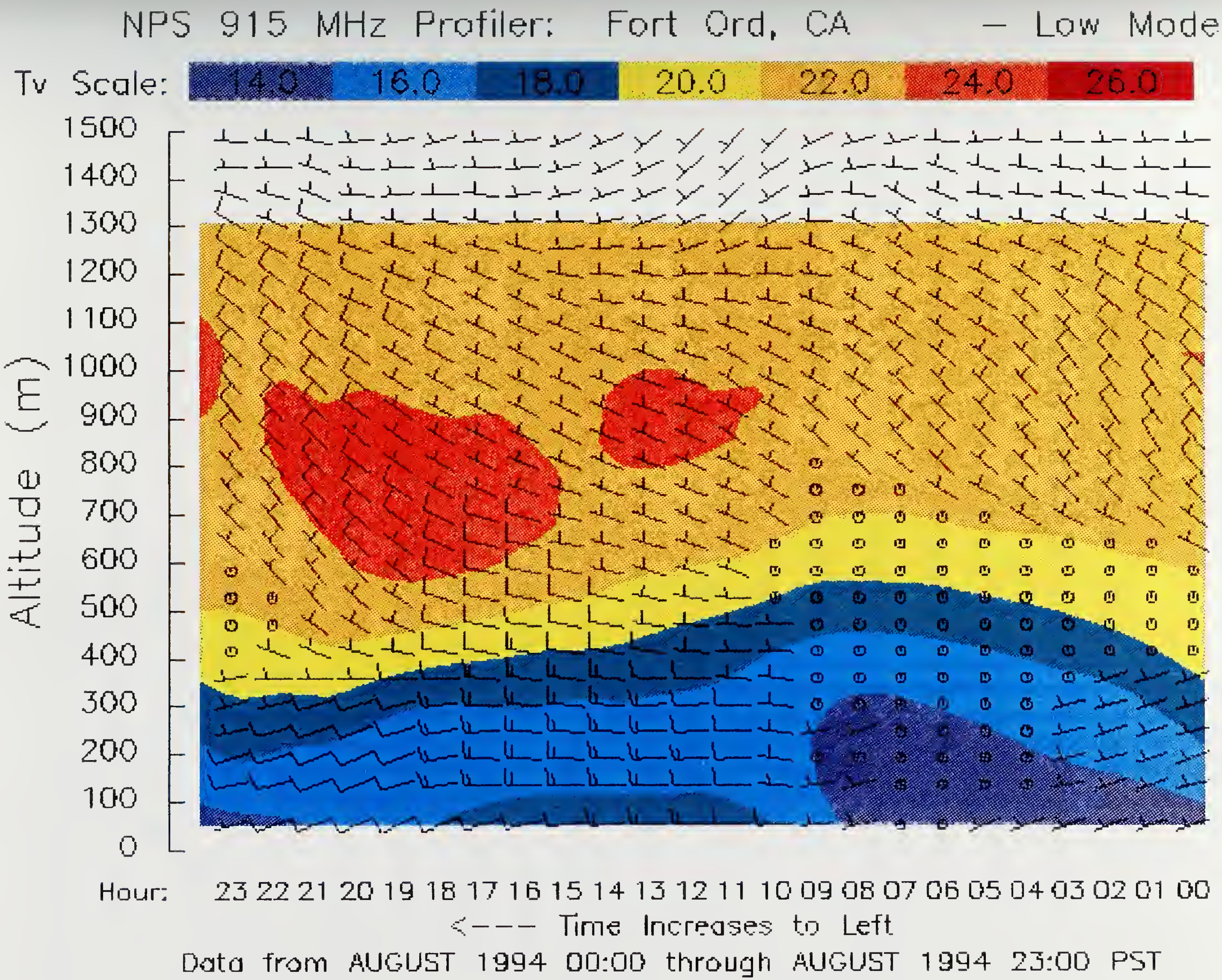

FIGURE 6.4 915-MHz wind profiler averages for 1-31 August 1994 at Fort Ord, CA. The data returns have 60 meter resolution.

that of the sea breeze. Using this reasoning the return flow should be 800 m in height and 1/2 the sea breeze speed or around 7-8 kts. The return flow could exist above 1500 m (vertical range of this profiler) however.

Typically in the canonical sea/land breeze scenario, one would expect the land breeze to be blowing offshore at night. However, these three average summer profiles depict no evidence of any land breeze. Previous research has found that frequent land breezes are not apparent in this region until beginning in September. All three months experienced their calmest wind periods in the lower 500 m during the early morning hours. 0400 PST was the calmest time for all three months.

2. Temperatures

The profiler for June depicts the existence of a large-scale subsidence inversion (Figure 6.1). The strong subsidence inversion is found between 500 and 1200 m. This significant inversion is the result of the descending warm air from the semi-permanent subtropical high pressure system located off the central California coast. The warmest air (22°C) exists in the inversion from 600 to 900 m during the afternoon (1330 to 2030 PST). The diurnal temperature range at the surface is small ranging from 12.0°C (0400 PST) to 17.1°C (1400 PST). A diurnal temperature range of 5.1°C is common for summertime in this region.

July's temperature Figure (6.3) shows a stronger subsidence inversion. Also, unlike the month of June, July's subsidence inversion undergoes little diurnal modulation throughout the 24 h observation period. The maximum temperature inversion in July was (26.0°C) and continued during the entire day. This region of warm temperatures extended from 900 to 1300 m. July also reached its maximum surface temperature of 17.1 °C at 1400 PST. Its minimum temperature of 12.8 °C occurs at 0400 PST for a daily range of 4.3 °C. The reduced diurnal temperature range was due to more extensive low cloudiness during the month.

The inversion duration and location in August are strikingly similar to those in June (Refer to Figure 6.4). The subsidence inversion in August attains a maximum temperature of (26.0°C) from 1100 to 2200 PST. A maximum vertical range exceeds 1500 m with higher temperatures aloft occurring from 550 to 1000 m. Surface temperatures exceeded 18 °C during the afternoon cooling to 13 °C at night.

The month of June shows a diurnal modulation of the inversion. The 16.0-18.0°C isotherms indicate a height maximum of 320 m at 0700 and a minimum height of 160 m in the evening at 1830 PST. July 94 was characterized by extensive low clouds. This was determined by a radiometer measuring 373 Watts/meters^2 of long-wave solar irradiance at the Fort Ord site. These clouds prevented the month of July from receiving as much solar heating. Therefore there is little diurnal signal in July's inversion height; however, as a result of these low clouds emitting the infrared radiation at night, July's night temperatures are warmer than June and August. August's diurnal inversion change is similar to June.

3. Comparisons to Other Studies

The numerous studies investigating the LASBEX data in 1987 provide some data to compare with the profiler's observations. The sea-breeze onset times at Fort Ord obtained by the 915-MHz profiler agree well with previous studies such as Fagan's (1988) who determined an average onset time for the sea breeze to be 0942 PST with a range of 0844

PST to 1030 PST. Intrieri's et al. (1990) preliminary study on 16 September 1987 first detected onshore flow at 0920 PST with the NOAA Doppler lidar. Maximum surface winds occurring in the early afternoon hours during the summer of 1994 at Fort Ord were consistent with previous LASBEX findings. Banta et al. (1993) using both Doppler lidar and Doppler sodar found the strongest winds in the sea breeze occur at the surface. Their study found winds reaching a maximum at the surface attaining a speed of 9 m/s at 1229 PST on 27 September 1987.

The low-level sea-breeze circulation recorded by the wind profiler extended vertically to 420 m in the monthly average data. Previous case studies have found significant depth for the sea-breeze circulation. Banta's et al. (1993) found a depth extending as high as 1 km while Fagan's (1988) study of 10 cases in September 1987 observed an average of 659 meters. Naturally the monthly averaging in this study has a larger number of observations and will provide a more typical sea-breeze depth.

Utilizing the maximum vertical range of the wind profiler, no return flow was observed during the summer below 1500 m. Intrieri et al. (1990) were also unable to detect any clearly defined return flow in Monterey Bay in 1987. Banta's et al. (1993) postulated that strong synoptic forcing and complex inland topography cause the return flow to be either incorporated into the slope/valley local wind systems, or being absorbed into the deep inland convective boundary layer.

An inability to observe any clockwise turning of the winds by the wind profiler at low-levels or in examining the aloft winds of the monthly averages confirms the lack of Coriolis turning in Monterey Bay documented by other studies. These past studies detected no Coriolis turning: Yetter (1990), Shaw and Lind (1989), and Banta et al. (1993). Banta's el at. (1993) concluded that an absence of recirculation (return flow) prevents Coriolis forcing from having the requisite time required to act upon the sea-breeze circulation.

C. SANTA CRUZ PROFILER SITE

1. Winds

The Santa Cruz profiler site was located at Longs Marine Lab near the city pier in Santa Cruz. This is the only site during the REINAS Project that did not have a co-located RASS system. The average winds for the month of June 1994 at the Santa Cruz site are found in Figure (6.5). These winds depict the influence of a diurnal sea breeze occurring from the surface up to a height of 700 m. At the surface, the sea breeze first shows an onshore component then veers to a westerly direction by 1000 PST with a magnitude of 10 kts. During the month of June, the strongest surface winds were 14 kts for a two hour period (1300 to 1500 PST). A mean land breeze is not depicted in the average data.

The afternoon winds of the sea breeze extend vertically from the surface to 480 m. Unlike the Fort Ord site, strongest winds remain at the surface throughout the afternoon. Above 100 m the sea breeze winds never exceed 6 kts. Below 500 m the winds average to calm from 1800 to 0900 PST. The Santa Cruz mountains run parallel to the coast and block flow below 500 m except for the sea-breeze circulation.

Above 500 m the large-scale flow is northwesterly and it is present throughout the 24 h period. The effect of the mesoscale flow upon the synoptic flow is not to change the direction of the larger flow but to rather reduce its magnitude. During the hours the sea

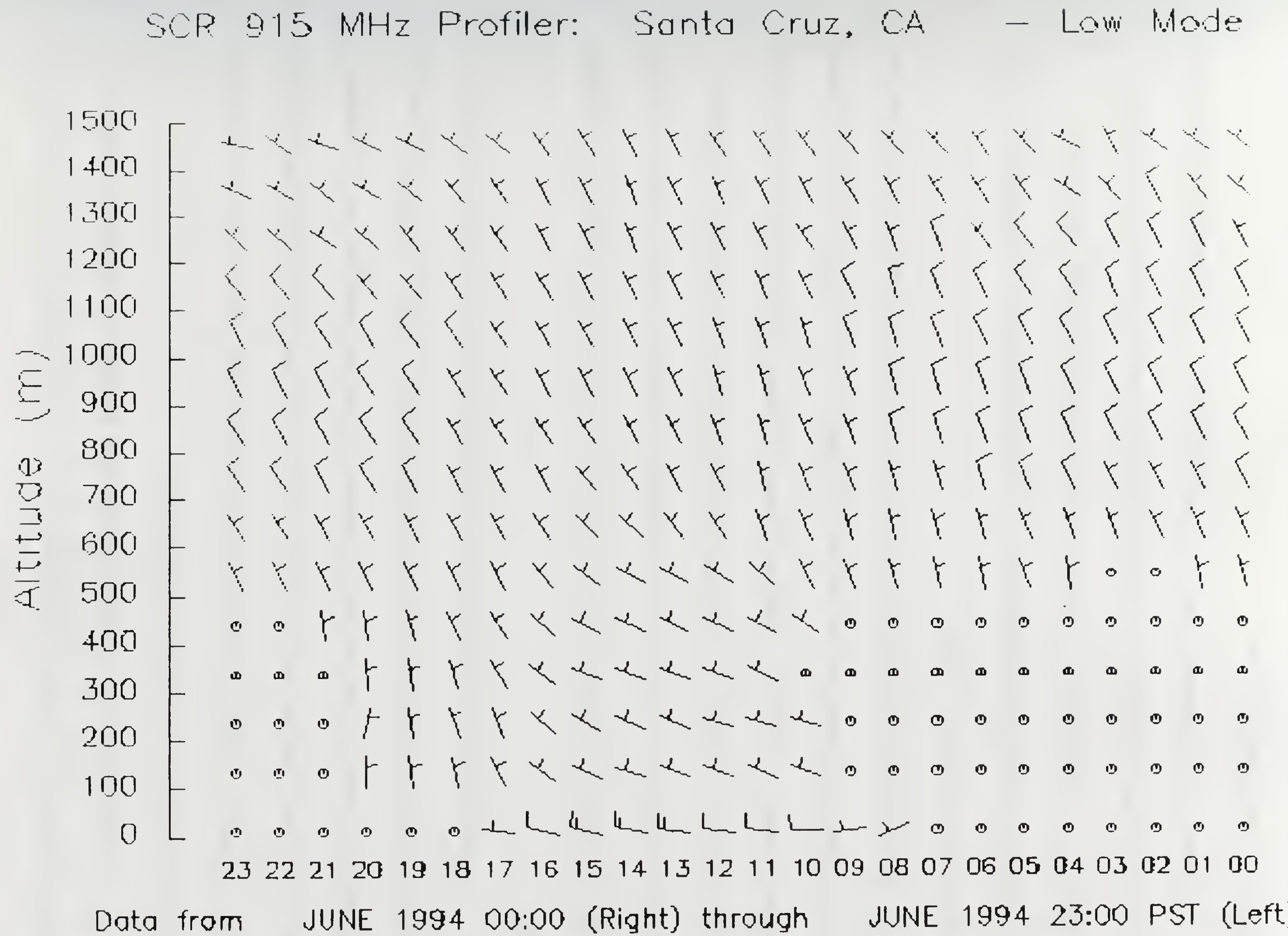

FIGURE 6.5 915-MHz wind profiler averages for 1-30 June 1994 at Santa Cruz, CA. The RASS system was not available at this location. The data returns have 100 meter resolution.

breeze is active, the upper-level flow reduces from 10 to 5 kts. Stronger flow is present during the evening and night hours.

Evidence of a large-scale, upper-level, sea-breeze flow as witnessed at the Fort Ord site is more difficult to discern. A very slight backing of the flow (5-10°) occurs between 700 and 1500 m. Additionally, the reduction of the synoptic flow from 10 to 5 kts as previously discussed suggests the existence of this large-scale flow. The magnitude of this circulation is approximately .5 m/s.

The wind pattern during the month of July at Santa Cruz differs from the winds in June, especially at levels below 500 m (Refer to Figure 6.6). The month of July experiences a sea breeze onset at 1000 PST. July's sea breeze circulation was more short-lived lasting only from 1000 to 1800 PST. The upper-level synoptic flow is weaker when compared with June reaching only 10 kts for a few hours during the night. Surface winds in July had a maximum speed of 10 kts from 1200 to 1700 PST. These winds are confined to the lowest 100 m.

August's average wind data showed a continued reduction in intensity from July with the sea breeze at the surface lasting only from 1000 to 1700 PST (Refer to Figure 6.7). Flow above 500 m in August was almost identical to the upper level flow in July. August, like July, also had maximum surface winds of 10 kts, but these winds started later and ended earlier, lasting from 1200 until 1500 PST. In all three months, the strongest winds in the sea-breeze circulation were located at the surface.

No evidence of Coriolis turning was detected during any of the three summer months in Santa Cruz. Backing of the winds aloft to approximately 10 to 15° did occur

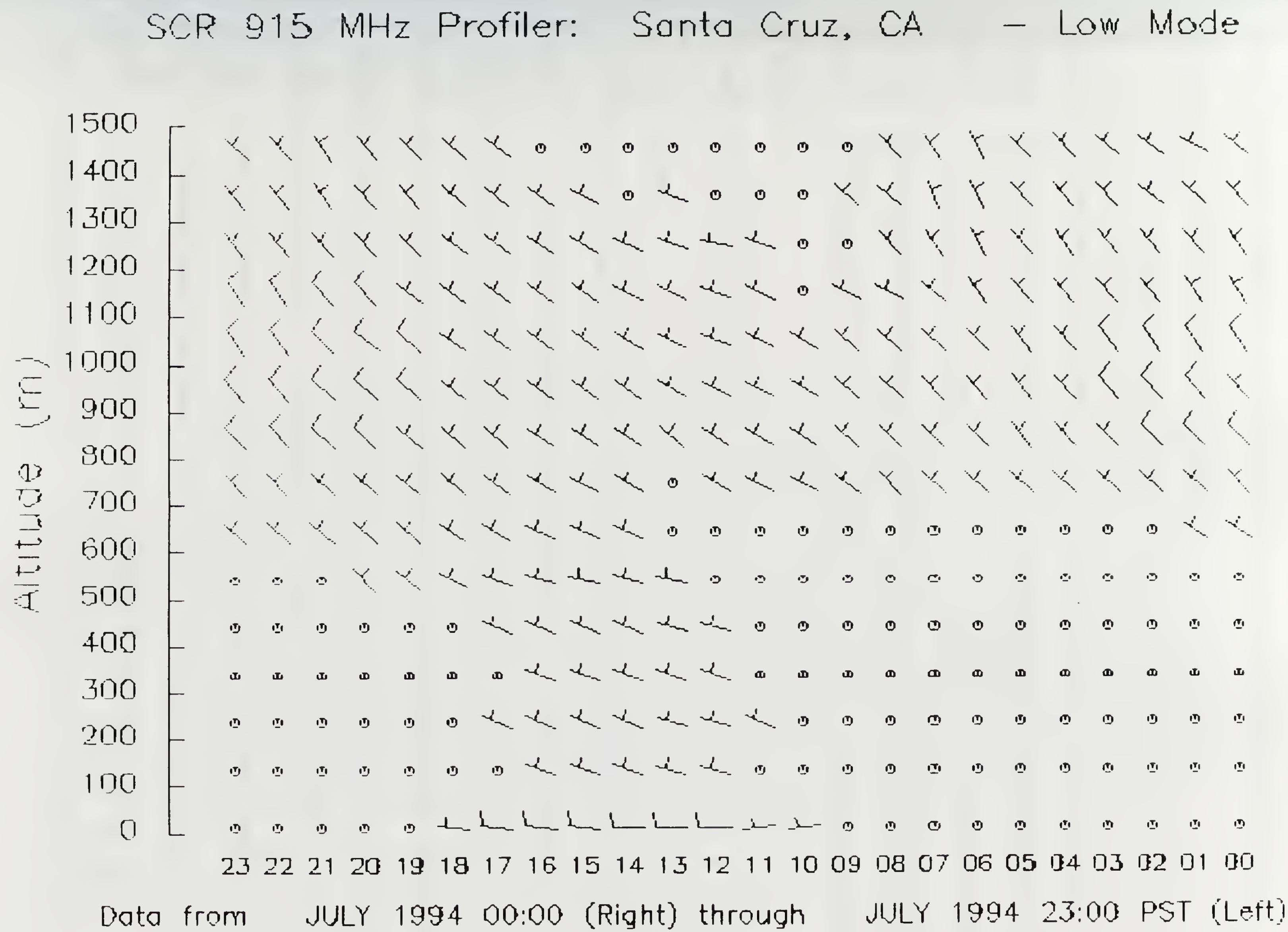

FIGURE 6.6 915-MHz wind profiler averages for 1-31 July 1994 at Santa Cruz, CA. The RASS system was not available at this location. The data returns have 100 meter resolution.

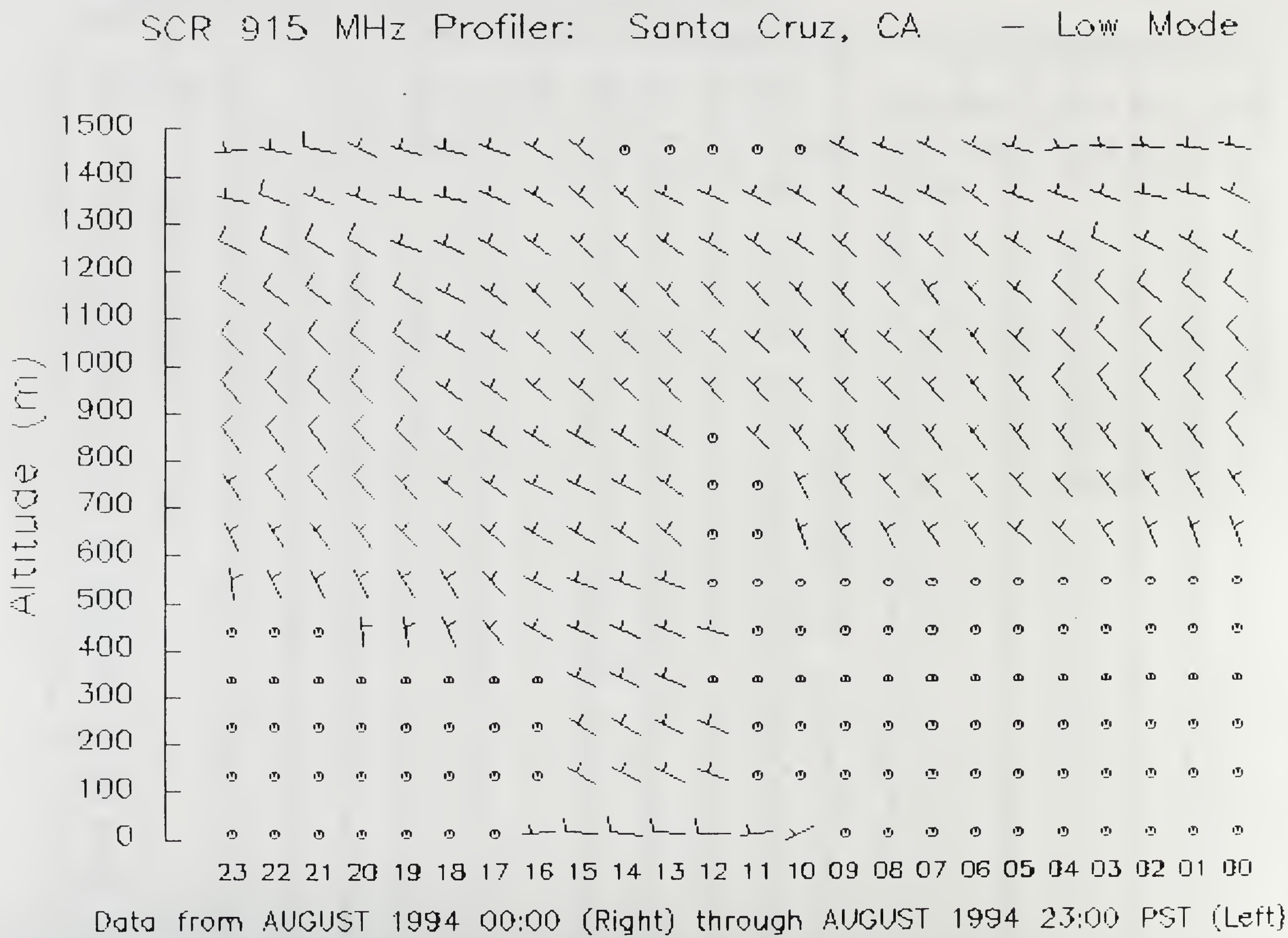

FIGURE 6.7 915-MHz wind profiler averages for 1-31 August 1994 at Santa Cruz, CA. The RASS system was not available at this location. The data returns have 100 meter resolution.

during the hours of the sea-breeze circulation. Some veering of the winds did occur in the month of June below 400 m from 1800 to 2000 PST. This veering could be the result of topographical channeling of the mature sea breeze.

The main sea breeze difference between the Fort Ord site and the Santa Cruz site was the weaker intensity at Santa Cruz. Additionally, the distinct 20-30° backing of the winds aloft at Fort Ord (600-900 m) were not observed at Santa Cruz. The backing of the winds at this location was more in the range of 10 to 15°. The low-level wind pattern at the Fort Ord site was also more intense then at the Santa Cruz site. The sea-breeze circulation at Santa Cruz was found in the lowest 100 m where at Fort Ord this circulation extended up to 400 m.

D. POINT SUR PROFILER SITE

1. Winds

The data received from the wind profiler site at the Point Sur Naval Station covers from 20-31 July 94 and all of August 94 (Refer to Figures 6.8, and 6.9). The average wind depicts a diurnal a strengthening of the northwest flow during the 20-31 July observation period. Surface data shows strengthening of the winds from 10 kts during the night and morning to 15 kts during the afternoon. In July, the synoptic winds are from the northwest with no indication of turning due to mesoscale circulation influence. Above 900 m the average winds are less than 2.5 kts. The steep coastal topography seems to be impeding any flow at these higher levels. Below 500 m a maximum of 10 kts occurs in these low-level regions exclusive of the 15 kts experienced at the surface. During the night, the winds do not decrease in intensity as seen at the other sites, but maintain 10 kts

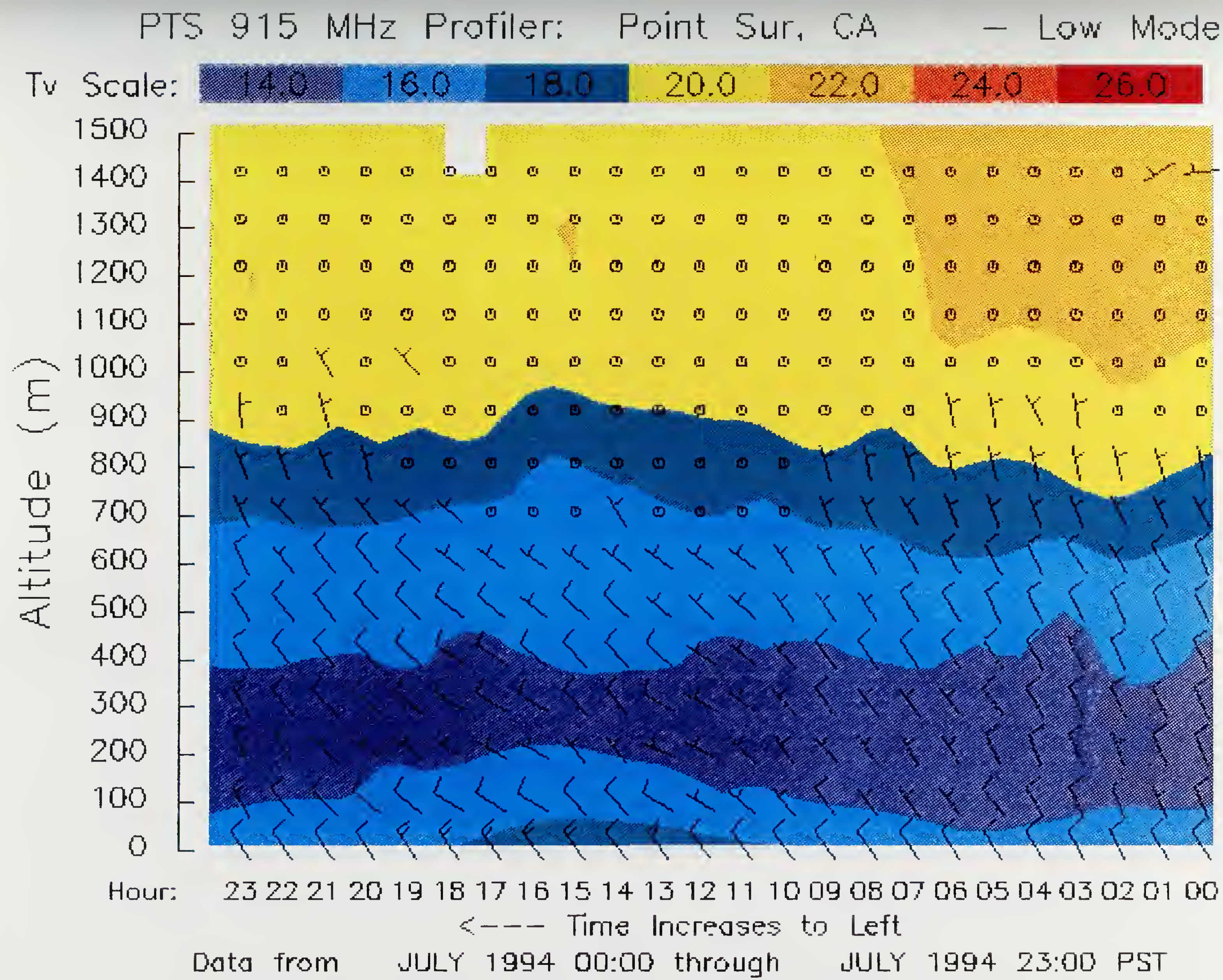

FIGURE 6.8 915-MHz wind profiler averages for 1-31 July 1994 at the Point Sur Naval Station. The data returns have 100 meter resolution.

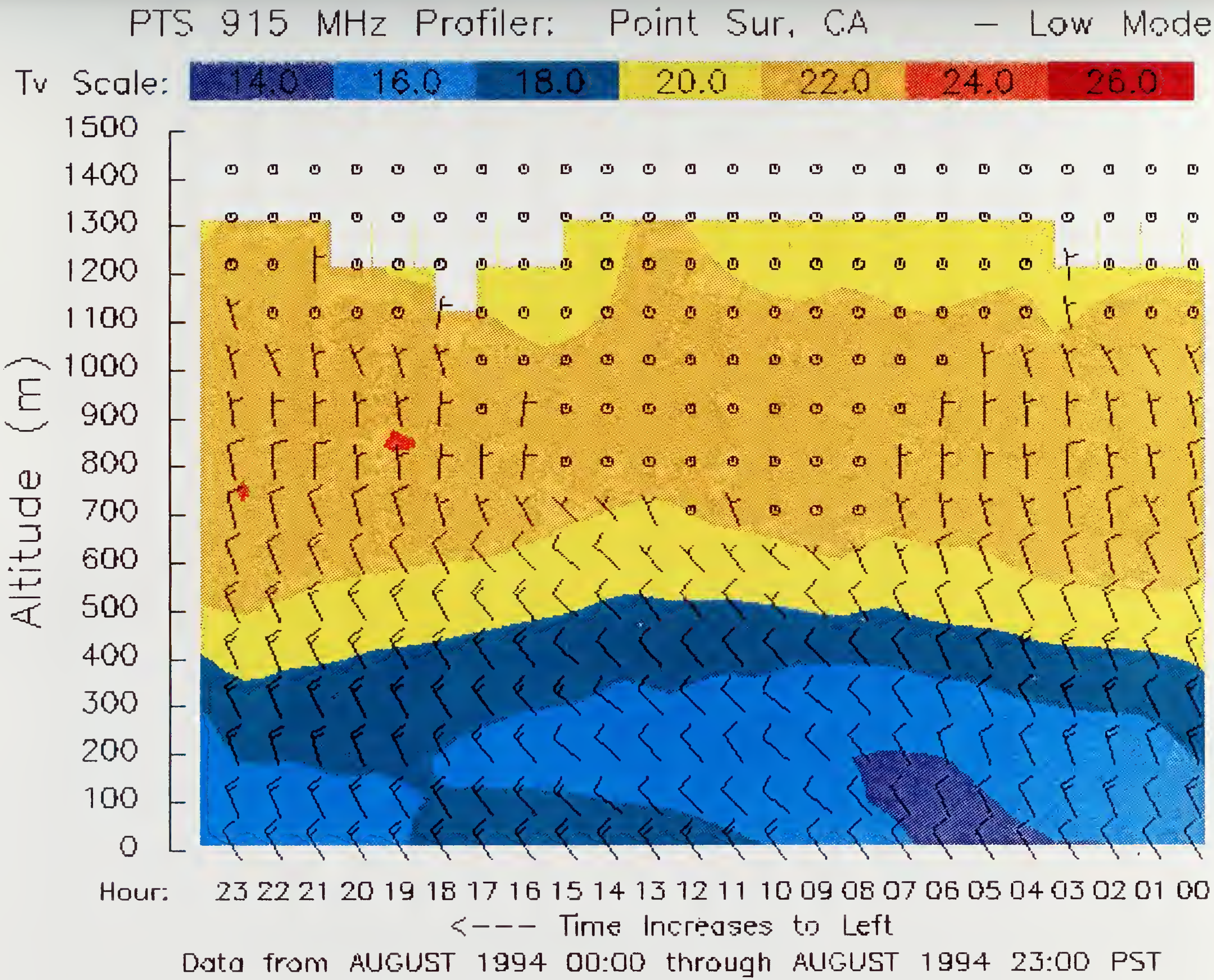

FIGURE 6.9 915-MHz wind profiler averages for 1-31 August 1994 at the Point Sur Naval Station. The data returns have 100 meter resolution.

The wind pattern during August at the Point Sur profiler site is similar to July in that a clearly defined sea-breeze circulation is not apparent. Surface wind strengthens to 15 kts at 1000 PST and maintains this speed until 2200 PST. Below 500 m, the winds in August are stronger in magnitude than the winds in July. Wind in excess of 15 kts exist below 500 m from 1500 to 0300 PST.

A slight backing of the winds does occur in July from 1000 to 1800 PST. This backing of the winds is approximately 10° and is strongest between 200 to 600 m. Any clockwise turning of the winds due to Coriolis forcing is not apparent during the month of July. Additionally, any return flow or land breeze is not discernible during this month. August is similar to July in that this month also encounters some slight backing of the winds from 0800 to 1500 PST, the normal sea-breeze circulation hours. As in the July profile, August has no detectable average return flow or average land- breeze circulation

2. Temperatures

The profiler for July depicts the existence of a strong temperature inversion. This large scale subsidence inversion exists throughout the 24 h observing period and starts at approximately 400 m and continues to the RASS system's vertical limit of 1500 m. The inversion temperatures are nearly constant except for the warming experienced above 1100 m from 0000 to 0700 PST. In August, the inversion is lower and stronger than the one in July. Temperatures exceed 22°C aloft during the entire 24 hour period. Cooler temperatures in August (those below 18°C) exist only below 500 m. In July, they continued up to 900 m

There is no appreciable diurnal variation of the inversion during the month of July

The heating that occurs in the late afternoon hours does cause some warming of the air column near the surface. The only distinguishing diurnal change that occurs in July is the heating above 1000 m that occurs from 0000 to 0700 PST.

The inversion and the depth of the marine atmospheric boundary layer do show some diurnal changes. The inversion is higher during the afternoon and lower at night. This behavior plus the warmer inversion temperatures at night (See Figure 6.8) suggests the presence of a topographical circulation that is downward at night and upward during the day. More data is needed to confirm this behavior.

3. Comparisons with Previous Along Coast Studies

Beardsley et al. (1987) examined the data from the Coastal Ocean Dynamics Experiment (CODE), which was conducted during the summer of 1981 and 1982. This study carried out along the central and northern California coast studied the strong coastal California temperature inversion. A potential temperature difference of 10°C across this inversion marks the boundary between the subsiding dry, warm air above and the cool, moist air in the marine layer below. A mean inversion height of 400 m was documented along the coast with a sharp rise in height moving to the west. The observations from the Point Sur profiler site are consistent with the Beardsley study.

The CODE data documented air flow in the marine boundary layer to be characterized by periods of strong (7-15 m/s), upwelling favorable along-shelf winds from the northwest. These northwest winds would blow consistently for periods lasting up to 30 days and then be interrupted by shorter periods of much weaker southerly winds that blow for 2 to 4 day periods. Beardsley et al. (1987) found that the maximum winds are located just below this inversion base. Since this thesis study is of monthly averages any anomalous southerly winds would be nullified by the dominating northerly flow. However, the profile from August clearly depicts the maximum winds of 15 kts occurring just below the inversion a 500 m. At this inversion boundary the winds are reduced from 15 to 10 kts within 100 m, clearly marking the boundary layer described in the Beardsley study.

E. HOLLISTER PROFILER SITE

1. Winds

The Hollister profile site is important in this study because it is the only inland location. Situated 25 km form the coast, the sea breeze should not be as pronounced as at a coastal location. The onset of the sea-breeze circulation in Hollister occurs at 1100 PST for June (Refer to Figure 6.10). Since the sea breeze has to travel an additional 25 km to get to the Hollister profile site, later onset times of about 1.0-1.5 hours are to be expected. This time was determined using an average speed of 8 m/s from Round's (1993) study of sea-breeze front propagation in Monterey Bay. The maximum strength of the sea breeze circulation in June is 10 kts at the surface. The strong surface winds last from 1200 to 1700 PST.

The maximum depth of the sea-breeze circulation in Hollister is more difficult to ascertain than at the coastal stations. The sea breeze is observed as an initial westerly flow that becomes more northwesterly after 1600 PST. The peak in the average wind is 10 kts at the surface occurring from 1300 to 1600 PST. The clearest evidence of a sea breeze is in the modification of the predominantly northwest synoptic flow that occurs between 1100 to 1500 PST below 500 m. It is during this time the wind is backing from the

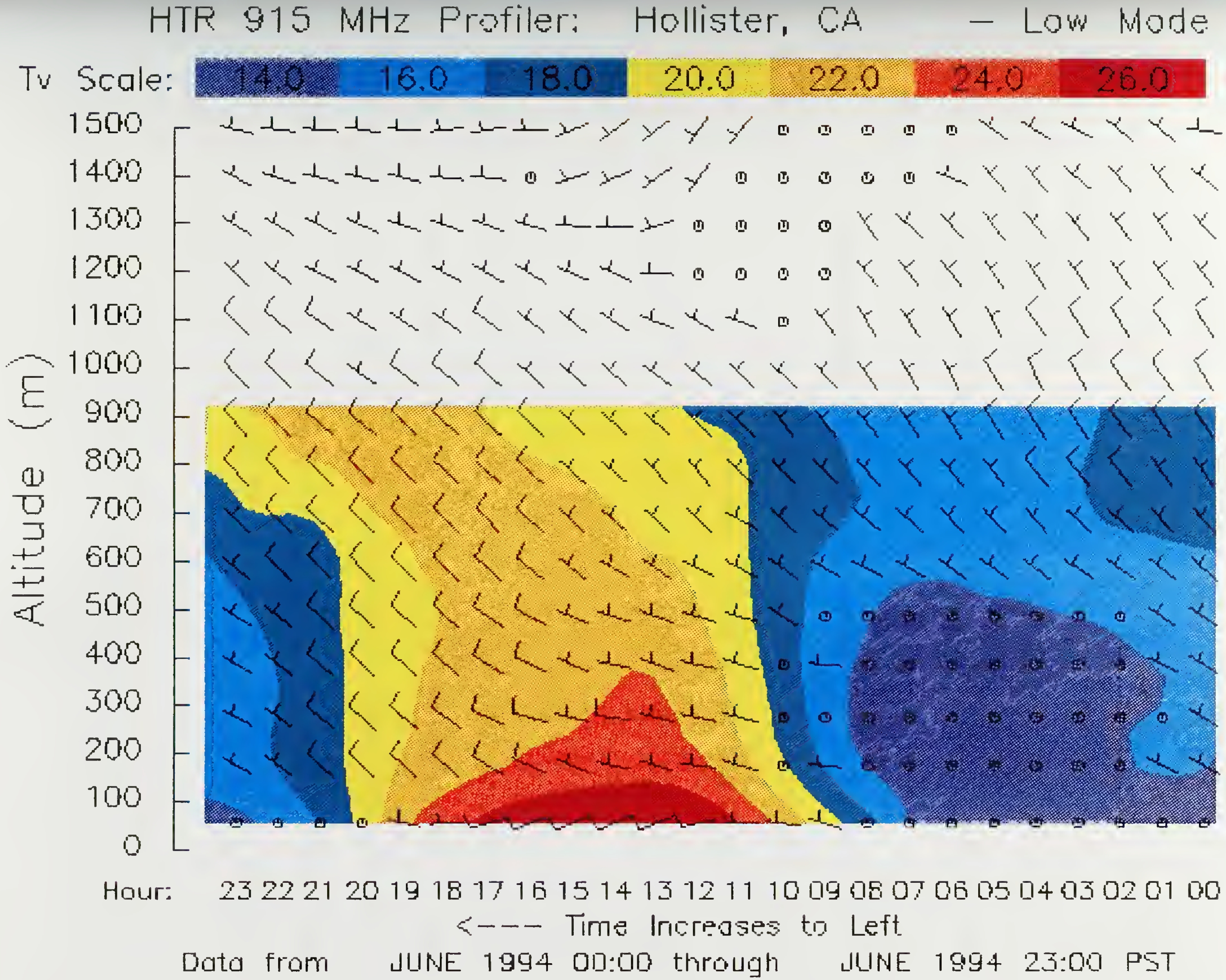

FIGURE 6.10 915-MHz wind profiler averages for 1-30 June 1994 at Hollister, CA. The data returns have 100 meter resolution.

northwest to westerly flow. During the month of June no backing of the winds occurs above 500 m.

The prevailing synoptic flow during the month of June is from the northwest. Upper-level flows are westerly at heights of 1300 to 1500 m in the evening. Low-level winds are calm until 1100 PST when they pick up from a westerly direction. No Coriolis turning was noted at any levels during June in Hollister but some backing of the winds above 1300 m is apparent. Lack of an average land breeze and average return flow is also noted in June.

The wind pattern during July in Hollister has longer periods of calm below 500 m (Refer to Figure 6.11). The only wind activity below 500 m during this month is the result of the sea breeze that arrives in the late morning. July has an onset time 1 h earlier than June, occurring at 1000 PST. The maximum surface winds in July reach 10 kts from 1300 to 1700 PST.

The upper-level July winds are characterized by northwesterly wind from the late evening to the early morning. Prior to the onset of the sea breeze, calm winds extend from 1000 to 1500 m aloft. Once the sea breeze is initiated, its modifying effect on the synoptic flow is felt to 1500 m. Besides the 10 kt winds observed at the surface during the early afternoon, the July data shows some 10 kt winds aloft above 800 m in the evening starting at 1700 PST. Additionally, no average return flow or average land breezes are detectable in July.

Above 800 m some evidence of the large-scale continental sea breeze is found. In the synoptic flow between 800 and 1500 m the hourly average winds are backing 20° to

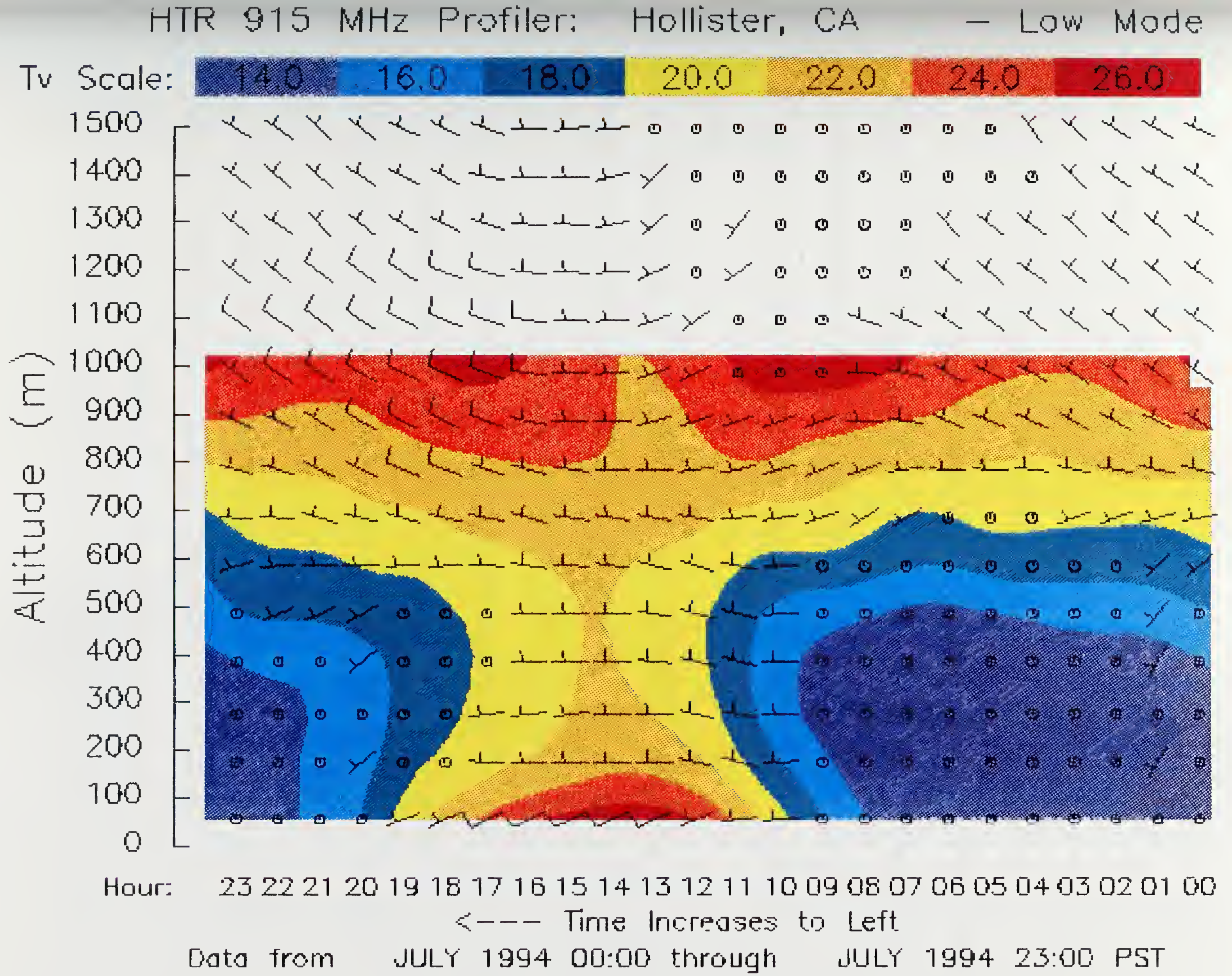

FIGURE 6.11 915-MHz wind profiler averages for 1-31 July 1994 at Hollister, CA. The data returns have 100 meter resolution.

30° to more westerly direction during the afternoon and become more northerly at night. The magnitude of this circulation is less than 1 m/s.

Average winds and temperatures for the month of August 1994 at the Hollister profiler site are presented in Figure (6.12). A sea-breeze onset time of 1100 PST is observed. The sea breeze is strongest at the surface where winds strengthen to 10 kts at 1300 PST and maintain this speed to 1600 PST. Aloft 5 kt winds are common.

A region of 5 kt afternoon winds that extend up to 800 m after sea-breeze onset and continue to increase to a height of 1400 m at 1600 PST. The strongest sea-breeze winds are confined below 100 m during the month of August and the significant upward development witnessed at the Fort Ord site is not experienced at the inland Hollister location.

August's winds are predominately from the northwest. Some westerly winds are found in the late evening above 1100 m and westerly sea breeze winds at the surface are present in the early afternoon hours. From 0000 to 1000 PST calm winds extent from the surface up to 600 m and from 0700 to 1300 PST calm winds extent aloft from 1000 to 1500 m. No evidence of an average land breeze or an average return flow is evident during this month. Above 1000 m, evidence of the large-scale continental sea breeze is also found.

2. Temperature

The range of the RASS system was consistently 900 to 1000 m at the Hollister site. Deep radiative cooling exists in June from 2030 to 0900 PST. Cooling to 14.0°C reaches up to 500 m in the early morning hours. Evidence of a subsidence inversion is more difficult to discern due to the 900 m vertical range of the RASS system at this location

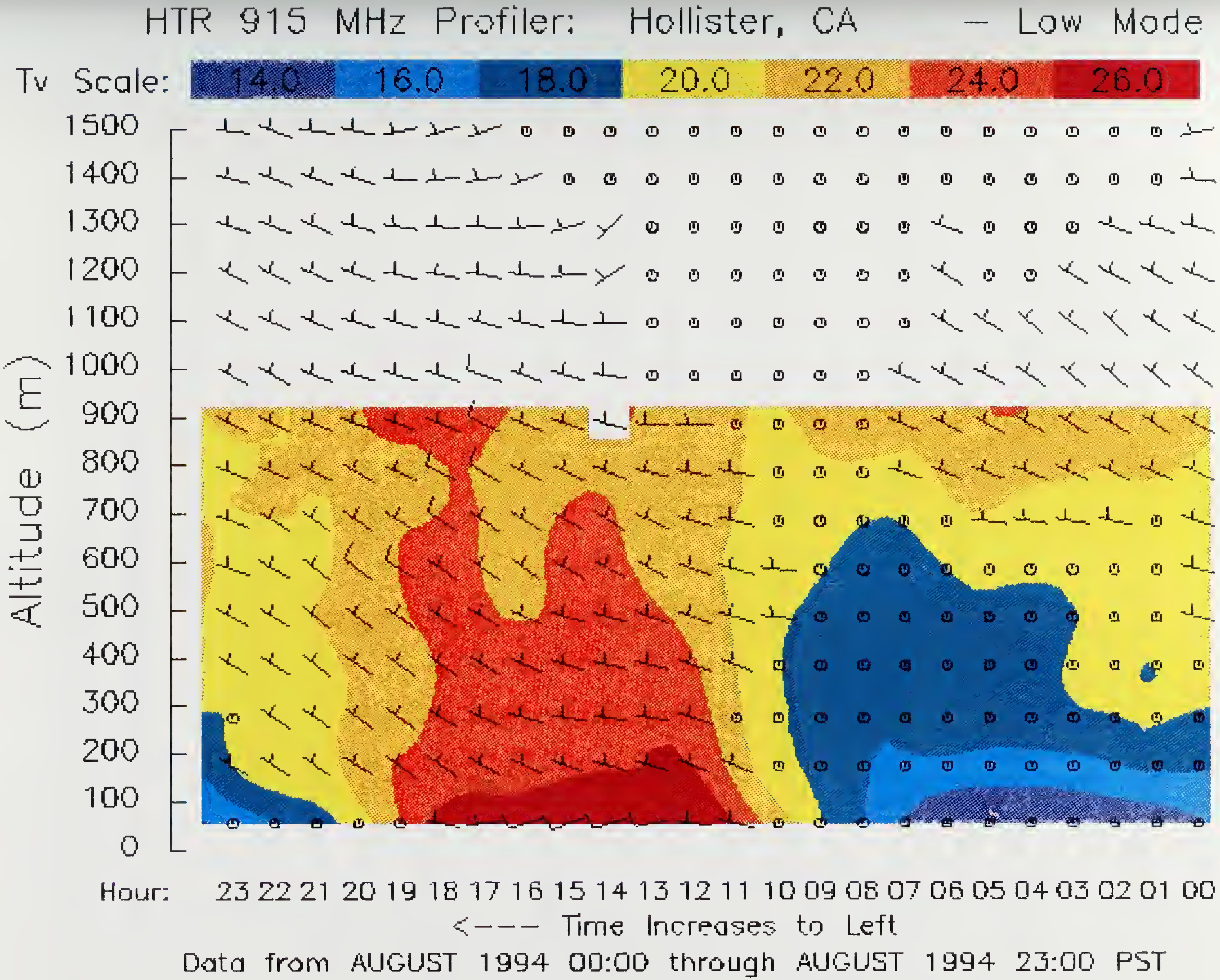

FIGURE 6.12 915-MHz wind profiler averages for 1-31 August 1994 at Hollister, CA. The data returns have 100 meter resolution.

However, in July a strong subsidence inversion exists for the entire day reaching temperatures in excess of 26.0°C at 1000 m. August experiences less radiative cooling than both June and July. This nighttime cooling lasts from 2200 to 0900 PST and extends only to 100 m. A subsidence inversion exits in August, however its hard to differentiate due to the 900 m limit on the RASS system.

All three months in Hollister undergo a similar heating pattern. Cooling during the night creates an area of low temperatures. Heating in the early afternoon warms the vertical air column up to 900 m. No diurnal variation of the inversion is detectable in July and August.

A maximum surface temperature of 26.9°C occurs during June at 1400 PST. A low temperature of 10.1°C occurs during this month at 0500 PST. July experienced its maximum temperature of 25.7°C at 1400 PST. The low temperature for July is 13.3°C and it occurs at 0400 PST. August's minimum and maximum temperatures are 13.5°C and 28.7°C respectively. The high temperature occurs at 1400 PST and the low temperature occurs at 0400 PST.

In Hollister the evidence of a sea-breeze circulation is more difficult to detect than in Fort Ord. The onset times at the Hollister site should lag the Fort Ord site from 1.5 to 2.0 hours. Since the sea breeze arrived early in Fort Ord in July, it is expected to arrive earlier at the Hollister site also. As expected, the onset time at the Hollister site in July was at 1000 PST 1 h before the June and August onset times of 1100 PST.

The maximum surface winds and the height are considerably less at the Hollister profiler site than those at Fort Ord. The Hollister maximum surface winds are 10 kts in July vice 15 kts in July at Ft Ord. Additionally, these 15 kts winds are felt at 400 m unlike Hollister where the maximum sea breeze winds aloft only reach 5 kts. Hollister and Fort Ord have weaker surface winds in June and August.

The boundary of the sea-breeze circulation is harder to define in Hollister than in Fort Ord. In Fort Ord there is a distinct magnitude change in the winds usually from 15 kts to 10 kts, however in Hollister the sea breeze is contained closer to the surface and is more difficult to differentiate from the ambient winds. The time of maximum depth is the same at both Hollister and Fort Ord typically occurring between 1500 and 1600 PST. By 1800 PST any influence of the sea breeze is gone in Hollister.

F. QUARTERLY WIND AVERAGES

The quarterly plots of the four profiler sites provide good representations of the long term interactions between the mesoscale sea-breeze circulation and the prevailing large-scale flow. The quarterly plot from the Fort Ord site best typifies a canonical sea breeze scenario with synoptic onshore flow (Refer to Figure 6.13). The winds are predominately northwest except at low-levels when the westerly sea breeze is blowing. A larger scale sea breeze is responsible for a 20 to 30 ° backing of the large scale winds up to the 1500 m vertical limit of this profiler. The diurnal modulation of the inversion is readily discernable.

Santa Cruz's quarterly plot illustrates how limited the sea breeze is at this location (Refer to Figure 6.14). Acting only from 1100 to 1600 PST, this is the only wind activity below 500 m. During this observation period there is minimal turning of the winds above 700 m. The Santa Cruz mountains effectively block any low-level large scale flow and strongly suppress the sea-breeze circulation other than in the early afternoon.

The Point Sur location had the most northerly winds out of any of the profiler sites. The steep topography that meets the coast in this location furnishes a blocking barrier forcing the winds to blow northerly (Refer to Figure 6.15). The strongest winds were also located at this site. Situated just below the marine inversion boundary at 500 m these 15 kt winds were present from 1600 to 0300 PST. This profile is in agreement with the marine inversion jet described in the Beardsley et al. (1987) study.

Strong radiative heating during the day is clearly depicted in Hollister's quarterly plot (Refer to Figure 6.16). The cooler air brought in by the sea breeze at other locations does not reach this inland location. Additionally, Hollister experiences greater levels of cooling at night. The winds are consistently northwesterly at this location and periods of calm winds predominate the night hours to 700 m.

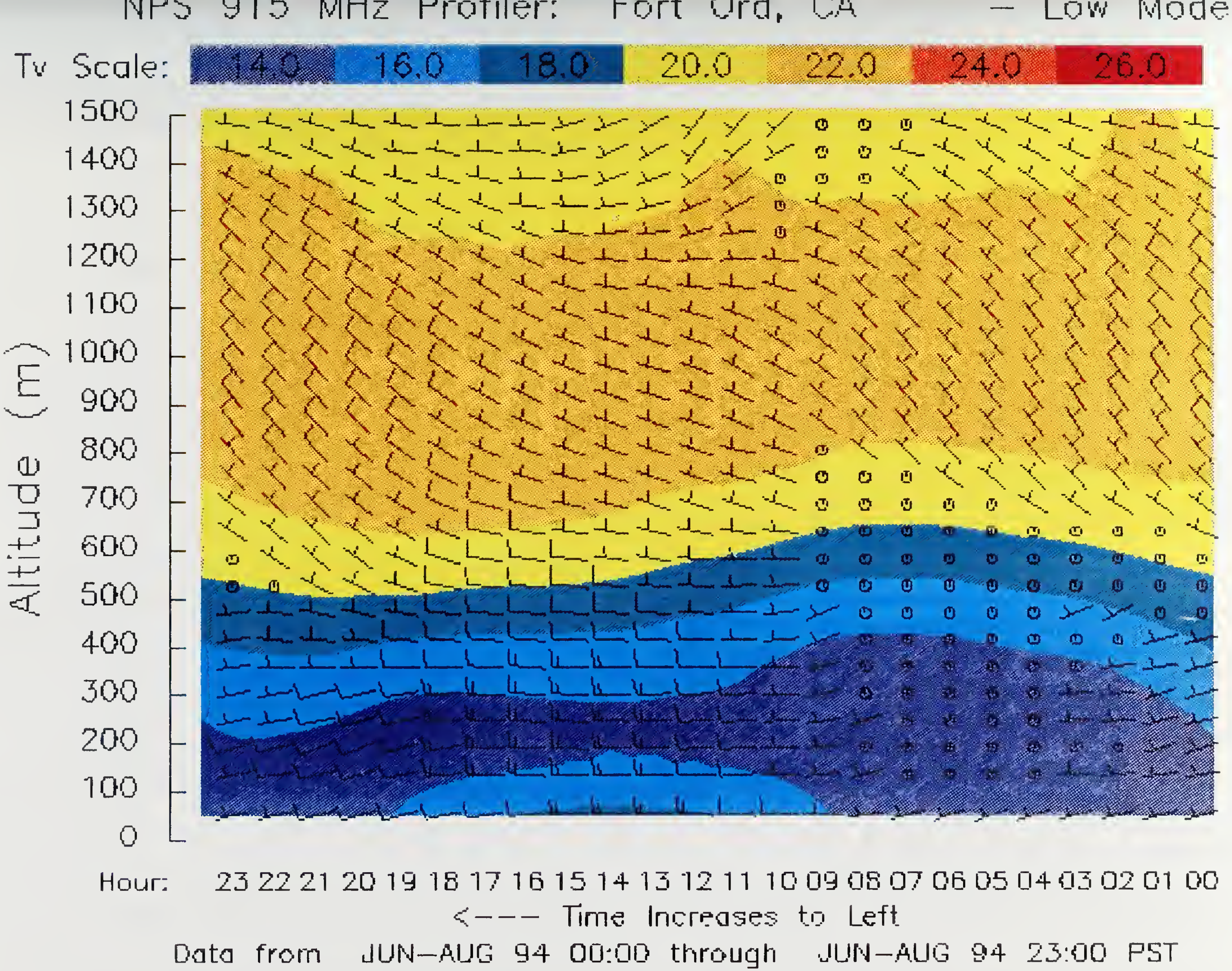

FIGURE 6.13 915-MHz wind profiler averages for June-August 1994 at Fort Ord, CA. The data returns have 60 meter resolution.

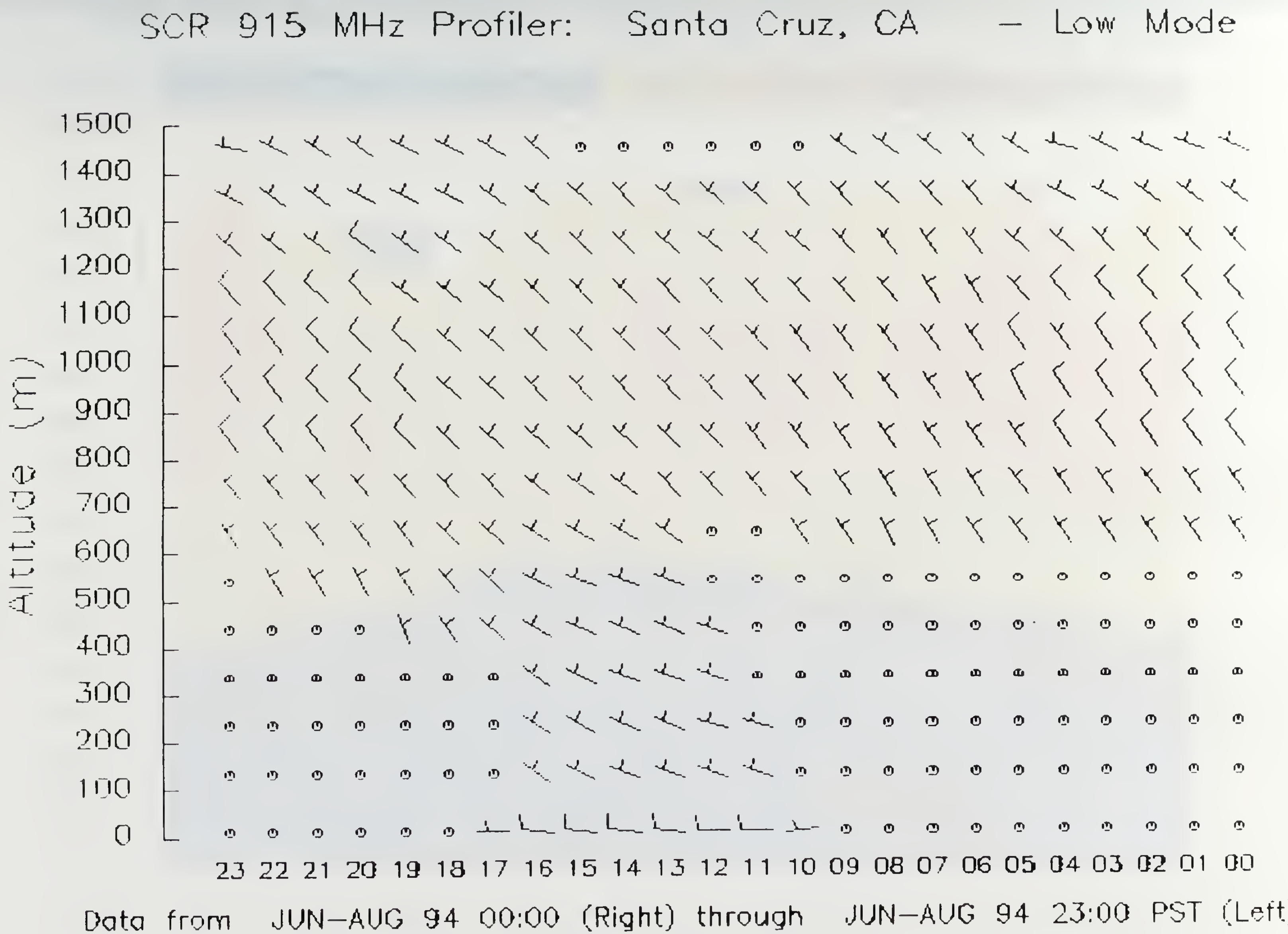

FIGURE 6.14 915-MHz wind profiler averages for June-August 1994 at Santa Cruz, CA The RASS system was not available at this location The data returns have 100 meter resolution

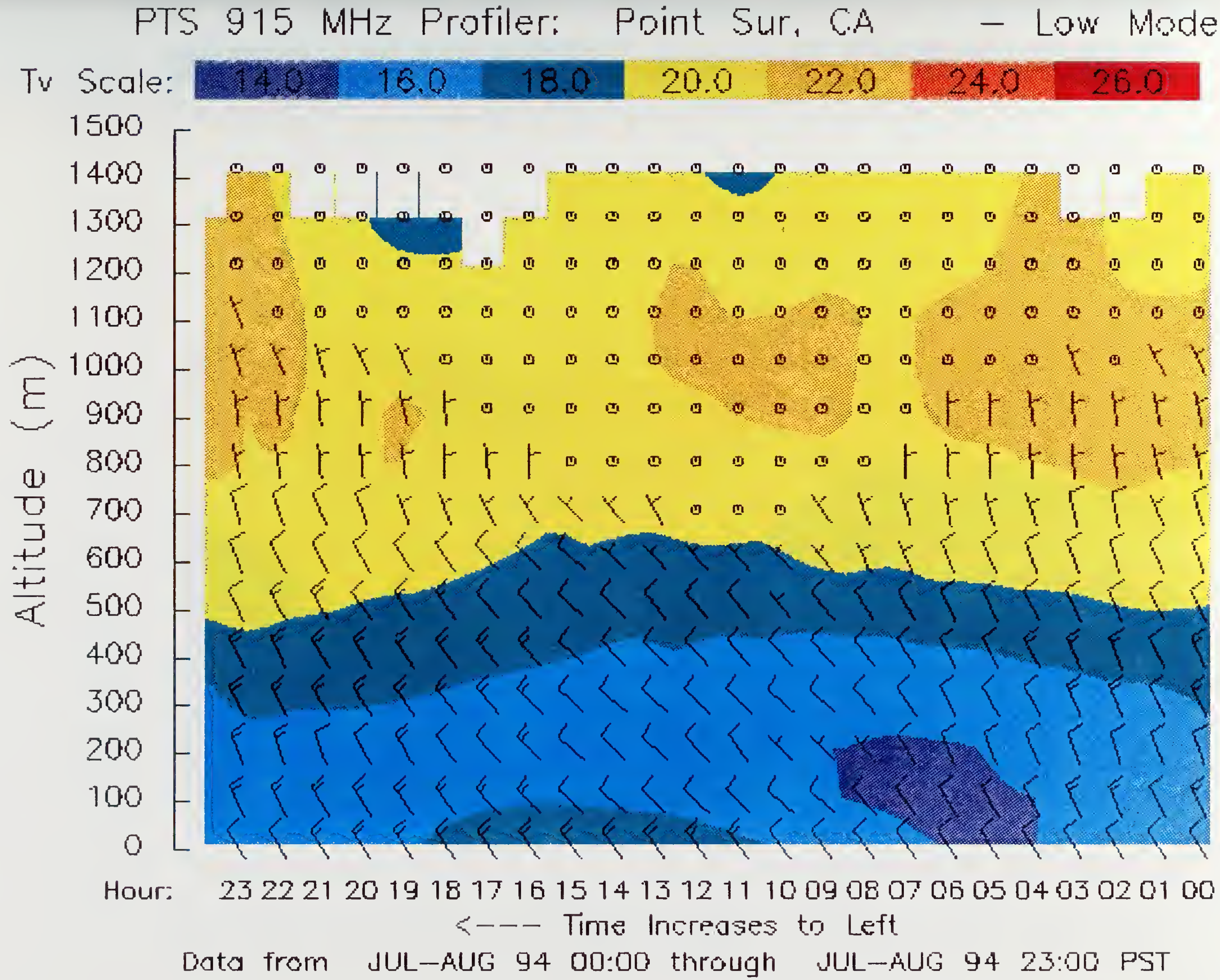

FIGURE 6.15 915-MHz wind profiler averages for July-August 1994 at the Point Sur Naval Station. The data returns have 100 meter resolution.

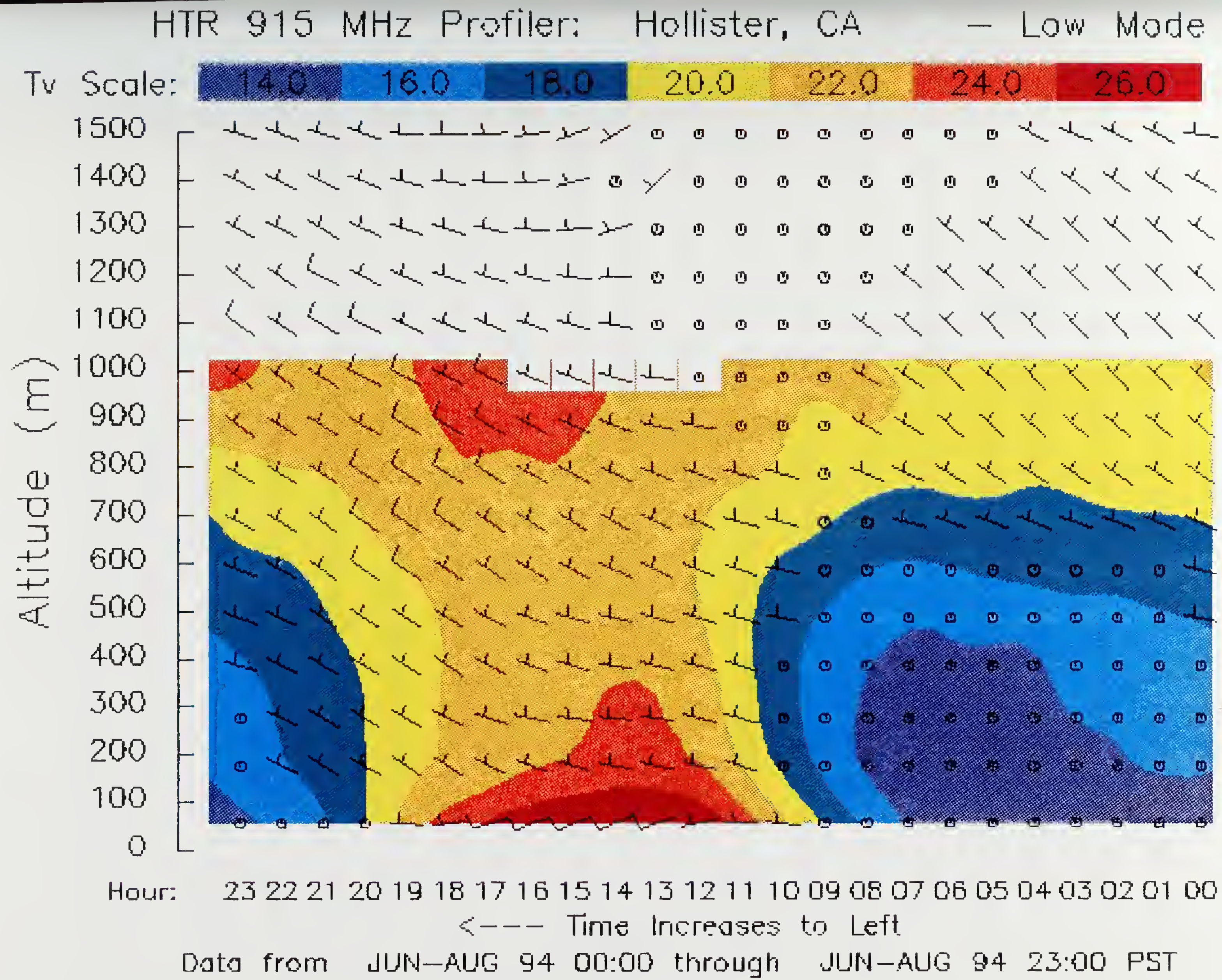

FIGURE 6.16 915-MHz wind profiler averages for June-August 1994 at Hollister, CA. The data returns have 100 meter resolution.

VII. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

In utilizing four different profiler sites located around Monterey Bay, this thesis studied the diurnal variations related to the mesoscale sea/land breeze wind. Monthly average graphical representations of the data provided a useful tool in categorizing recurring patterns the data sets. Overall the complex topography found in this region was the dominant modifying effect upon the sea-breeze circulation. This situation is best emphasized in the Point Sur profile, which showed a diurnal wind maximum along the coast due to the coastal mountain barrier. Additionally, features such as sea-breeze onset time, time of maximum winds, sea breeze maximum depth, and virtual temperature distribution with height were easily discernable from the monthly profiles. Various features of the sea-breeze circulation observed during LASBEX and other studies in the Monterey Bay region were reexamined in this thesis. The continuous coverage and accuracy afforded by the 915-MHz wind profiler and RASS system enabled verification of these earlier studies.

An indication of the modifying effects of marine stratus were demonstrated at the Fort Ord profiler site in July 94. During this month a large percentage of cloudy days prevented significant heating required to force the diurnal modulation of the inversion heights. Thus July 94 was characterized by a constant inversion height as opposed to the months of June and August 94 where evidence of an inversion height fluctuation is clearly visible

Overall this thesis data confirms prior analysis of the dominating influence of the summer time large-scale flow in central California. When sea-breeze circulations do form, they are regular and predictable. Topography either enhances their formation as in the Fort Ord case or modifies them as was shown at Point Sur. Evidence of any compensatory return flow was not detectable at any of the four sites. Coriolis turning was not evident at low-levels in the monthly average. However, when the mean winds were removed, anomalous winds did demonstrate clockwise turning throughout the 24 h period at the 700 m level at Fort Ord. The large-scale winds were consistently from the northwest at all sites except during the late mornings and afternoons when the weaker mesoscale circulation tended cause a slight backing of the primary flow.

B. RECOMMENDATIONS

The data provided from the 915-MHz wind profiler/ RASS system in this thesis demonstrates that high spatial resolution analysis of the winds in the lower atmosphere is feasible for extended time periods. A thorough understanding of mesoscale phenomena attained by using the wind profilers can help solve aviation and other meteorological forecast problems. Potentially dangerous wind shears and downbursts that occur with disturbing regularity in the vicinity of aircraft approach patterns at major airports are extremely difficult to detect with existing techniques such as rawinsondes. A wind profiler/RASS system located at the airport would provide this vital information when prebriefing pilots on these dangers. Forecasters could also examine the profile soundings of airports upwind, to see how the atmosphere might be changing. Computer programs can then automatically calculate from the profiles a number of meteorological indexes that can aid the forecaster in determining the likelihood of thunderstorms, tornadoes, and hail. Wind profilers can also provide information that can aid in the prediction of fog, air pollution alerts, and the downwind mixing of strong winds.

Currently in the central United States a network of wind profilers is providing forecasters with hourly wind speed and wind direction information at 72 different levels in a column of air 16 km thick. Wind information from the profilers is also sent to the National Meteorological Center (NMC), where it is integrated into computer models used in preparing mid-range weather forecasts. To further expand the wind profilers use throughout the continental United States, a proposal is under review to modify radars currently under construction adding a clear-air capability. One hundred thirty-five Doppler radar units are being deployed at selected weather stations in the United States as part of a network called NEXRAD (*NEX*t Generation weather *RAD*ar). The NEXRAD system will be studied to determine their efficacy on detecting wind shear and downdraft near airports. If NEXRAD is successful, further funding for clear-air radar will likely be made available (Ahrens, 1994).

This thesis showed the ability of the 915-MHz wind profiler/RASS system to provide continuous detailed mesoscale analysis in a demanding marine environment. Combining the existing Automated Surface Observing System (ASOS) with newly installed clear-air wind profilers at major airports can provide the information necessary to prevent unexpected flight conditions for pilots. It also advances our understanding of local wind systems like the sea/land breeze.

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